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signalling (Art. 503) the resistance and electrostatic capacity of the cable have to be met by balancing against them an "artificial cable" consisting of a wire of equal resistance, combined with a condenser of equal capacity. Messrs. Muirhead constructed for duplexing the Atlantic cable a condenser containing 100,000 square feet (over two acres of surface) of tinfoil. Condensers are also occasionally used on telegraph lines in single working to obviate disturbances from earth currents. They are constructed by placing sheets of tinfoil between sheets of mica or of paraffined paper, alternate sheets of foil being connected together. The paper is the finest bank-wove, carefully selected to be free from minute holes. Two thicknesses, drawn through a bath of the purest paraffin wax heated till it melts, are laid between each foil and the next; care being taken to exclude air bubbles. When a sufficient number have been assembled hot they are put under pressure to cool, and afterwards adjusted. Small condensers of similar construction are used in connexion with induction coils (Fig. 135).

303. Practical Unit of Capacity. — Electricians adopt a *unit of capacity*, termed one **farad**, based on the system of electromagnetic units. A condenser of one farad capacity would be raised to a potential of one volt by a charge of one coulomb of electricity.* In practice such a condenser would be too enormous to be constructed; the earth itself, as an isolated sphere, has a capacity of only $\frac{1}{1400}$ of a farad. As a *practical unit* of capacity is therefore chosen the **microfarad**, or one millionth of a farad; a capacity about equal to that of three miles of an Atlantic cable. Condensers of only ¼ microfarad capacity are about equal to one nautical mile of cable. They contain about 1200 square inches of foil. The

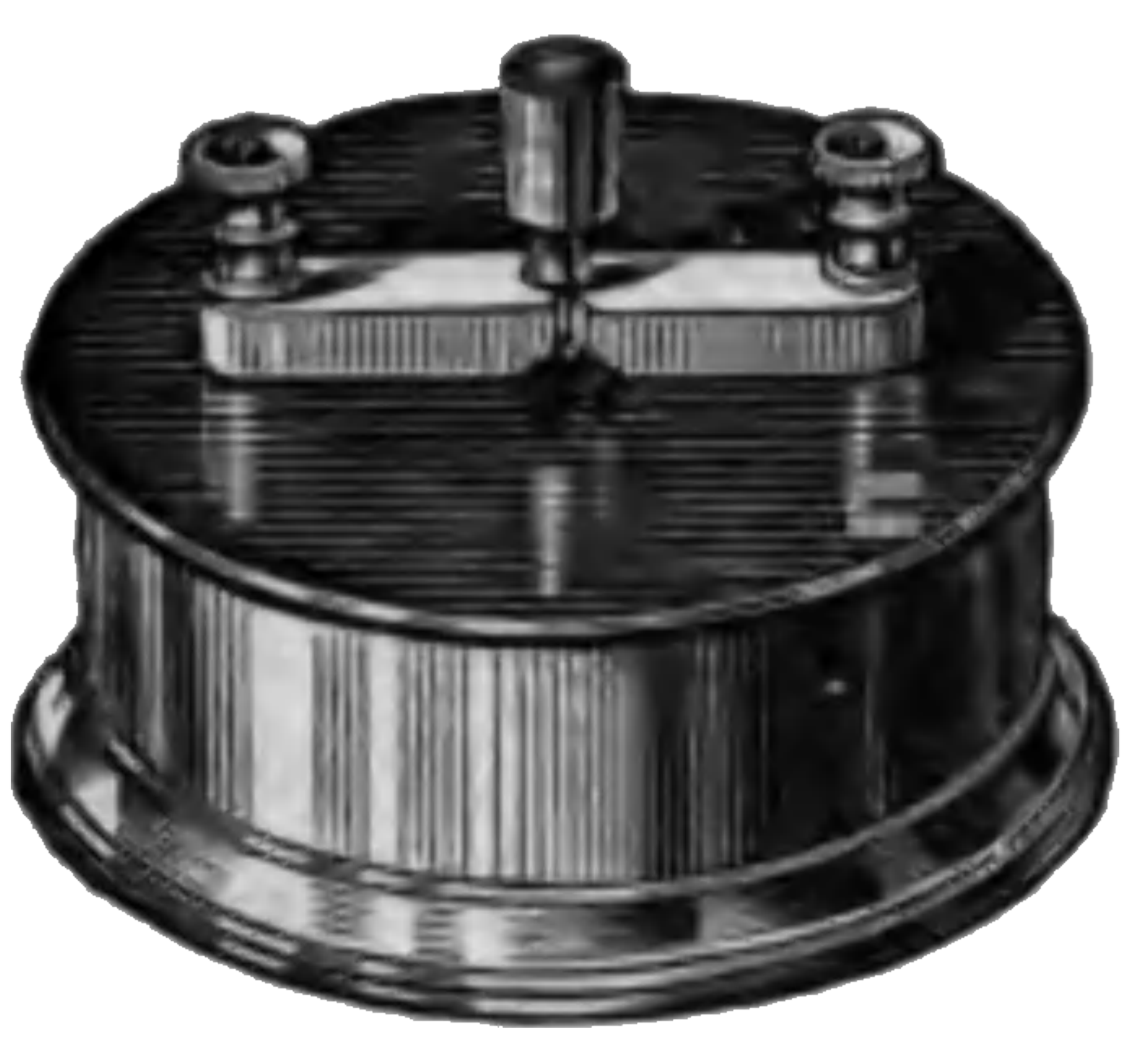


Fig. 159.

* See list of Practical Electromagnetic Units, Art. 354.

dielectric in them is usually mica, in thin sheets. Their general form is shown in Fig. 159. The two brass pieces upon the ebonite top are connected respectively with the two series of alternate sheets of tinfoil. The plug between them serves to keep the condenser discharged when not in use.

Methods of measuring the capacity of a condenser are given in Art. 418.

304. Formulæ for Capacities of Conductors and Condensers. — The following formulæ give the capacity of condensers of all ordinary forms, in electrostatic units: —

Sphere: (radius $= r$. See Art. 271).

$$K = r.$$

Two Concentric Spheres: (radii r and r', dielectric capacity, k).

$$K = k\frac{rr'}{r' - r}.$$

Cylinder: (length $= l$, radius $= r$).

$$K = \frac{l}{2\log_e\frac{l}{r}}.$$

Two Concentric Cylinders: (length $= l$, dielectric capacity $= k$, internal radius $= r$, external radius $= r'$).

$$K = k\frac{l}{2\log_e\frac{r'}{r}}.$$

Circular Disk: (radius $= r$, thickness negligible).

$$K = 2r/\pi.$$

Two Circular Disks: (like air condenser, Art. 56, radii $= r$, surface $= S$, thickness of dielectric $= b$, dielectric capacity $= k$).

$$K = kr^2/4b,$$

or

$$K = kS/4\pi b.$$

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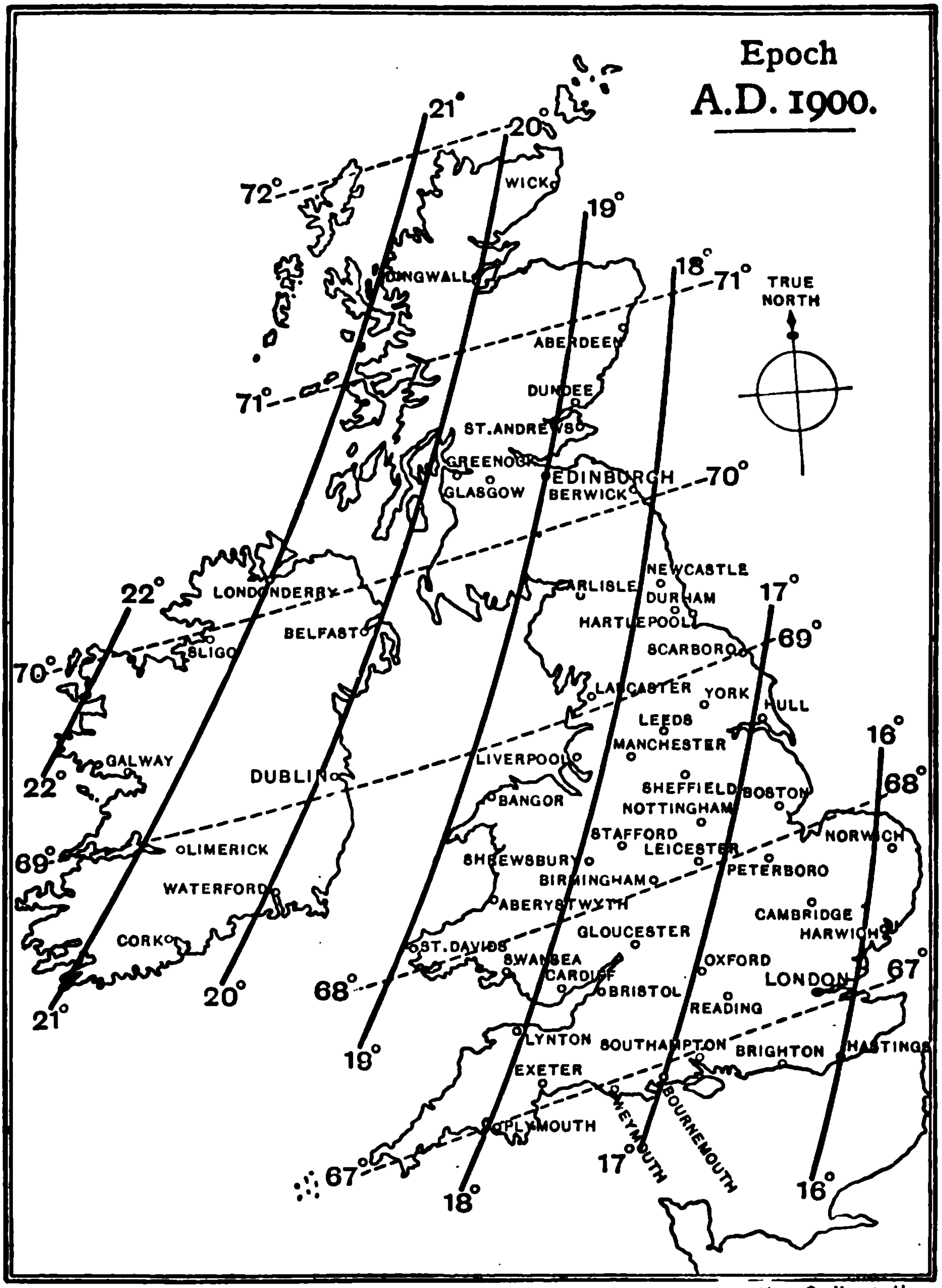
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ELEMENTARY LESSONS

IN

ELECTRICITY AND MAGNETISM

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MAGNETIC CHART OF THE BRITISH ISLANDS,

SHOWING THE LINES OF EQUAL MAGNETIC DECLINATION AND THOSE OF EQUAL MAGNETIC DIP.

ELEMENTARY LESSONS

IN

ELECTRICITY & MAGNETISM

BY

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PREFACE

THESE Elementary Lessons have now been largely re-written. The considerable changes made have been necessitated not only by the progress of the science but by the piracy, covert as well as open, to which since its appearance in 1881 the book has been subjected.

In the thirteen years which have elapsed much addition has been made to our knowledge, and many points then in controversy have been settled. The system of electric units, elaborated first by the British Association and subsequently in several International Congresses, is now legalized in the chief civilized countries. New magnetic surveys — in England by Thorpe and Rücker, in the United States under Mendenhall — have enabled new magnetic charts to be prepared for the epoch 1900 A.D. The researches of Ewing, Hopkinson, and others on the magnetic properties of iron, and the general recognition of the principle of the magnetic circuit, have advanced the science of magnetism, to which also Ewing's molecular theory has given an added interest. The properties of alternate currents, of which in 1881 little was known, have been forced into study by the extension of their industrial uses in telephony and in electric lighting.

Entirely new is the use of polyphase alternate currents and rotatory magnetic fields for the electric transmission of power. Transformers have come into extensive employment for the distribution at low-pressure of electric energy which has been transmitted from a generating station at high-pressure. Accumulators for the storage of electric energy have become of great commercial importance. Electric lamps, large and small, illuminate in millions our cities, towns, villages and ships. Electric currents for lighting and power are now supplied publicly on a very large scale from central stations operated by steam or water power. Supply-meters are in regular use, and measuring instruments of many forms have come into the market.

Along with these advances in practice there has been a no less striking progress in theory. The ideas of Faraday, as enlarged and developed by Clerk Maxwell, were in 1881 only beginning to be understood and appreciated outside a narrow circle. In 1894, thanks largely to the labours of Heaviside, Hertz, Lodge, Poynting, Fitzgerald, Boltzmann, Poincaré, and others, they are everywhere accepted. In 1881 Maxwell's electromagnetic theory of light — a conception not less far-reaching than the theory of the conservation of energy — was deemed of doubtful probability: it was not yet accepted by such great masters as Lord Kelvin or Von Helmholtz. Though adopted by the younger generation of British physicists, it needed the experimental researches of Hertz and of Lodge upon the propagation of electric waves to demonstrate its truth to their brethren in Germany, France, and America. Even now, after the most convincing experimental verifications

of Maxwell's splendid generalization that light-waves are really electric waves, many of the logical consequences of Maxwell's teaching are still ignored or misunderstood. It is still, to many, a hard saying that in an electric circuit the conducting wire though it guides does not carry the energy: that the energy-paths lie outside in the surrounding medium, not inside within the so-called conductor. That the guttapercha sheath, and not the copper wire within it, is the actual medium which conveys the impulse from one side of the Atlantic to the other in cable-telegraphy, is still incredible to those brought up in the older school of thought. But it is none the less a necessary consequence of the views which the inescapable logic of facts drove Maxwell and his followers to adopt.

This expansion of the science and of its practical applications has rendered more difficult than before the task of presenting with sufficient clearness, yet with necessary brevity, an elementary exposition of the leading phenomena, and of their relations to one another.

The author is under obligations to many scientific friends for data of which he has made use. He is under special obligations to his assistant, Mr. Miles Walker, for indefatigable proof-reading and revision of the Problems and Index.

LONDON, *September* 1894.



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ELEMENTARY LESSONS

ON

ELECTRICITY & MAGNETISM

Part First

CHAPTER I

FRICTIONAL ELECTRICITY

Lesson I.—*Electric Attraction and Repulsion*

1. Electricity.—*Electricity* is the name given to an invisible agent known to us only by the effects which it produces and by various manifestations called *electrical.* These manifestations, at first obscure and even mysterious, are now well understood; though little is yet known of the precise nature of eleotricity itself. It is neither matter nor energy; yet it apparently can be associated or combined with matter; and energy can be spent in moving it. Indeed its great importance to mankind arises from the circumstance that by its means energy spent in generating electric forces in one part of a system can be made to reappear as electric heat or light or work at some other part of the system; such transfer of energy taking place even to very great distances at an enormous speed. Electricity is apparently as indestructible as

matter or as energy. It can neither be created nor destroyed, but it can be transformed in its relations to matter and to energy, and it can be moved from one place to another. In many ways its behaviour resembles that of an incompressible liquid; in other ways that of a highly attenuated and weightless gas. It appears to exist distributed nearly uniformly throughout all space. Many persons (including the author) are disposed to consider it as identical with the luminiferous ether. If it be not the same thing, there is an intimate relation between the two. That this must be so, is a necessary result of the great discovery of Maxwell—the greatest scientific discovery of the nineteenth century—that light itself is an electric phenomenon, and that the light-waves are merely electric, or, as he put it, electromagnetic waves.

The name *electricity* is also given to that branch of science which deals with electric phenomena and theories. The phenomena, and the science which deals with them, fall under four heads. The manifestations of electricity when standing still are different from those of electricity moving or flowing along: hence we have to consider separately the properties of (i.) statical *charges*, and those of (ii.) *currents*. Further, electricity whirling round or in circulation possesses properties which were independently discovered under the name of (iii.) *magnetism*. Lastly, electricity when in a state of rapid vibration manifests new properties not possessed in any of the previous states, and causes the propagation of (iv.) *waves*. These four branches of the science of electricity are, however, closely connected. The object of the present work is to give the reader a general view of the main facts and their simple relations to one another.

In these first lessons we begin with charges of electricity, their production by friction, by influence, and by various other means, and shall study them mainly by the manifestations of attraction and repulsion to which they give rise. After that we go on to magnetism and

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About the year 1600, Dr. Gilbert of Colchester discovered by experiment that not only amber and jet, but a very large number of substances, such as diamond, sapphire, rock-crystal, glass, sulphur, sealing-wax, resin, etc., which he styled *electrics*,* possess the same property. Ever since his time the name **electricity** † has been employed to denote the agency at work in producing these phenomena. Gilbert also remarked that these experiments are spoiled by the presence of moisture.



Fig. 2.

3. Further Experiments. — A better way of observing the attracting force is to employ a small ball of elder pith, or of cork, hung by a fine thread from a support, as shown in Fig. 2. A dry warm glass tube, excited by rubbing it briskly with a silk handkerchief, will attract the pith-ball strongly, showing that it is highly electrified. The most suitable rubber, if a stick of sealing-wax is used, will be found to be flannel, woollen cloth, or, best of all, fur. Boyle discovered

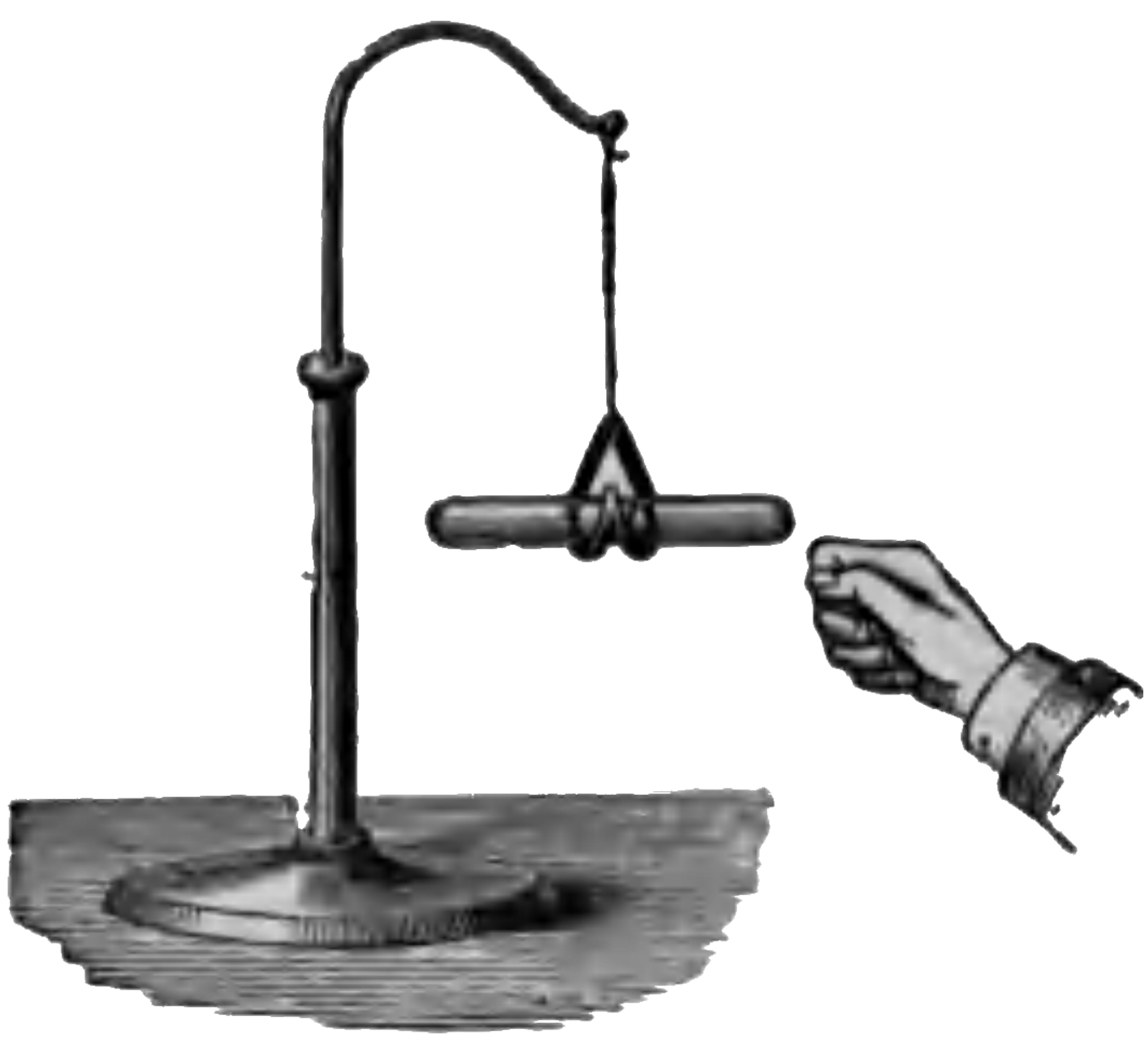


Fig. 3.

* "*Electrica*; quæ attrahunt eadem ratione ut electrum" (Gilbert).

† The first work in which this term was used is that of Robert Boyle, *On the Mechanical Production of Electricity*, published at Oxford in 1675.

that an electrified body is itself attracted by one that has not been electrified. This may be verified (see Fig. 3) by rubbing a stick of sealing-wax, or a glass rod, and hanging it in a wire loop at the end of a *silk* thread. If, then, the hand be held out towards the suspended electrified body, the latter will turn round and approach the hand. So, again, a piece of silk ribbon, if rubbed with warm indiarubber, or even if drawn between two pieces of warm flannel, and then hung up by one end, will be found to be attracted by objects presented to it. If held near the wall of the room it will fly to it and stick to it. With proper precautions it can be shown that *both* the rubber and the thing rubbed are in an electrified state, for both will attract light bodies; but to show this, care must be taken not to handle the rubber too much. Thus, if it is desired to show that when a piece of fur is rubbed upon sealing-wax, the fur becomes also electrified, it is better not to take the fur in the hand, but to cement it to the end of a glass rod as a handle. The reason of this precaution will be explained toward the close of this lesson, and more fully in Lesson IV.

A large number of substances, including iron, gold, brass, and all the metals, when held in the hand and rubbed, exhibit no sign of electrification,—that is to say, do not attract light bodies as rubbed amber and rubbed glass do. Gilbert mentions also pearls, marble, agate, and the lodestone, as substances not excited electrically by rubbing them. Such bodies were, on that account, formerly termed *non-electrics;* but the term is erroneous, for if they are mounted on glass handles and then rubbed with silk or fur, they behave as electrics.

4. Electric Repulsion.—When experimenting, as in Fig. 1, with a rubbed glass rod and bits of chopped paper, or straw, or bran, it will be noticed that these little bits are first attracted and fly up towards the excited rod, but that, having touched it, they are speedily repelled

and fly back to the table. To show this repulsion better, let a small piece of feather or down be hung by a silk thread to a support, and let an electrified glass rod be held near it. It will dart towards the rod and stick to it, and a moment later will dart away from it, repelled by an invisible force (Fig. 4), nor will it again dart towards the rod. If the experiment be repeated with another feather and a stick of sealing-wax rubbed on flannel the same effects will occur. But, if now the hand be held towards the feather, it will rush toward the hand, as the rubbed body (in Fig. 3) did.



Fig. 4.

This proves that the feather, though it has not itself been rubbed, possesses the property originally imparted to the rod by rubbing it. In fact, it has become electrified, by having touched an electrified body which has given part of its electricity to it. It would appear then that two bodies electrified with the same electrification repel one another. This may be confirmed by a further experiment. A rubbed glass rod, hung up as in Fig 3, is repelled by a

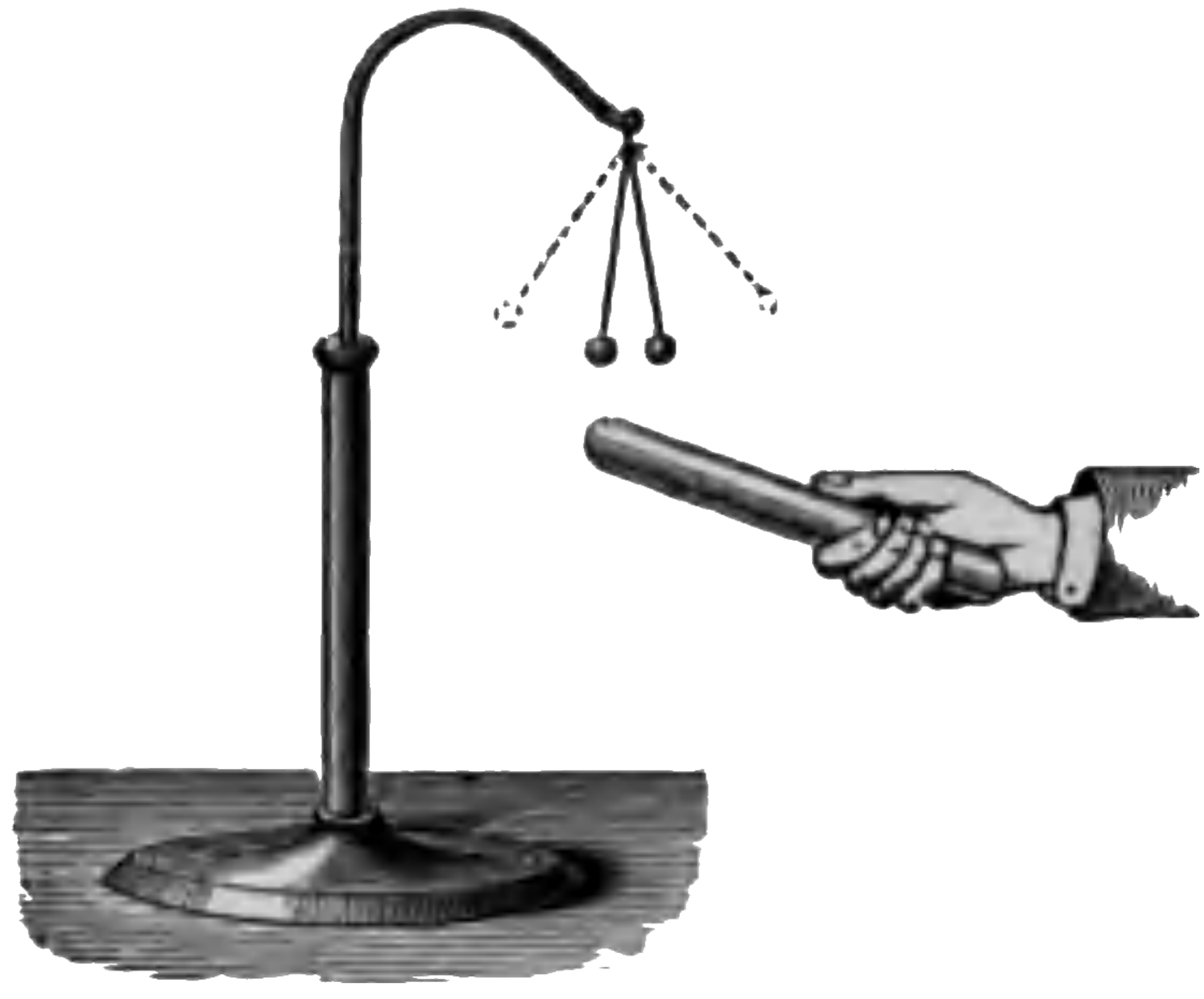


Fig. 5.

similar rubbed glass rod; while a rubbed stick of sealing-wax is repelled by a second rubbed stick of sealing-wax. Another way of showing the repulsion between two similarly electrified bodies is to hang a couple of small pith-balls, by thin linen threads to a glass support, as in Fig. 5, and then touch them both with a rubbed glass rod. They repel one another and fly apart, instead of hanging down side by side, while the near presence of the glass rod will make them open out still wider, for now it repels them both. The self-repulsion of the parts of an electrified body is beautifully illustrated by the experiment of electrifying a soap-bubble, which *expands* when electrified.

5. Two Kinds of Electrification.—Electrified bodies do not, however, always repel one another. The feather which (see Fig. 4) has been touched by a rubbed glass rod, and which in consequence is repelled from the rubbed glass, will be *attracted* if a stick of rubbed sealing-wax be presented to it; and conversely, if the feather has been first electrified by touching it with the rubbed sealing-wax, it will be attracted to a rubbed glass rod, though repelled by the rubbed wax. So, again, a rubbed glass rod suspended as in Fig. 3 will be attracted by a rubbed piece of sealing-wax, or resin, or amber, though repelled by a rubbed piece of glass. The two pith-balls touched (as in Fig. 5) with a rubbed glass rod fly from one another by repulsion, and, as we have seen, fly wider asunder when the excited glass rod is held near them; yet they fall nearer together when a rubbed piece of sealing-wax is held under them, being attracted by it. Symmer first observed such phenomena as these, and they were independently discovered by Du Fay, who suggested in explanation of them that there were two different kinds of electricity which attracted one another while each repelled itself. The electricity produced on glass by rubbing it with silk he called *vitreous* electricity, supposing, though erroneously, that glass could yield no

other kind; and the electricity excited in such substances as sealing-wax, resin, shellac, indiarubber, and amber, by rubbing them on wool or flannel, he termed *resinous* electricity. The kind of electricity produced is, however, found to depend not only on the thing rubbed but on the rubber also; for glass yields "resinous" electricity when rubbed with a cat's skin, and resin yields "vitreous" electricity if rubbed with a soft amalgam of tin and mercury spread on leather. Hence these names have been abandoned in favour of the more appropriate terms introduced by Franklin, who called the electricity excited upon glass by rubbing it with silk *positive* electricity, and that produced on resinous bodies by friction with wool or fur, *negative* electricity. The observations of Symmer and Du Fay may therefore be stated as follows:—Two positively electrified bodies apparently repel one another: two negatively electrified bodies apparently repel one another: but a positively electrified body and a negatively electrified body apparently attract one another. It is now known that these effects which appear like a repulsion and an attraction between bodies at a distance from one another are really due to actions going on *in the medium* between them. The positive charge does not really attract the negative charge that is near it; but both are urged toward one another by stresses in the medium in the intervening space.

6. Simultaneous Production of both Electrical States.—Neither kind of electrification is produced alone; there is always an equal quantity of both kinds produced; one kind appearing on the thing rubbed and an equal amount of the other kind on the rubber. The clearest proof that these amounts are *equal* can be given in some cases. For it is found that if both the − electricity of the rubber and the + electricity of the thing rubbed be imparted to a third body, that third body will show *no electrification at all*, the two equal and opposite electrifications having exactly neutralized each other. A simple

experiment consists in rubbing together a disk of sealing-wax and one covered with flannel, both being held by insulating handles. To test them is required an insulated pot and an electroscope, as in Fig. 29. If either disk be inserted in the pot the leaves of the electroscope will diverge; but if both are inserted at the same time the leaves do not diverge, showing that the two charges on the disks are equal and of opposite sign.

In the following list the bodies are arranged in such an order that if any two be rubbed together the one which stands earlier in the series becomes positively electrified, and the one that stands later negatively electrified:— *Fur*, *wool*, *ivory*, *glass*, *silk*, *metals*, *sulphur*, *indiarubber*, *guttapercha*, *collodion*, or *celluloid*.

7. **Theories of Electricity.** — Several theories have been advanced to account for these phenomena, but all are more or less unsatisfactory. Symmer proposed a "**two-fluid**" **theory**, according to which there are two imponderable electric fluids of opposite kinds, which neutralize one another when they combine, and which exist combined in equal quantities in all bodies until their condition is disturbed by friction. A modification of this theory was made by Franklin, who proposed instead a "**one-fluid**" **theory**, according to which there is a single electric fluid distributed usually uniformly in all bodies, but which, when they are subjected to friction, distributes itself unequally between the rubber and the thing rubbed, one having more of the fluid, the other less, than the average. Hence the terms *positive* and *negative*, which are still retained; that body which is supposed to have an excess being said to be charged with positive electricity (usually denoted by the *plus* sign +), while that which is supposed to have less is said to be charged with negative electricity (and is denoted by the *minus* sign −). These terms are, however, purely arbitrary, for in the present state of science we do not know which of these two states really means more and

which means less. In many ways electricity behaves as a weightless substance as incompressible as any material liquid. It is, however, quite certain that *electricity is not a material fluid*, whatever else it may be. For while it resembles a fluid in its property of apparently flowing from one point to another, it differs from every known fluid in almost every other respect. It possesses no weight; it repels itself. It is, moreover, quite impossible to conceive of two fluids whose properties should in every respect be the precise opposites of one another. For these reasons it is clearly misleading to speak of an electric fluid or fluids, however convenient the term may seem to be. In metals and other good conductors electricity can apparently move and flow quite easily in *currents*. In transparent solids, such as glass and resin, and in many transparent liquids such as oils, and in gases such as the air (if still, and not rarefied) electricity apparently cannot flow. Even a vacuum appears to be a non-conductor. In the case of all non-conductors electricity can only be moved by an action known as *displacement* (see Art. 57).

▲ It appears then that in metals electricity can easily pass from molecule to molecule; but in the case of non-conductors the electricity is in some way stuck to the molecules, or associated with them. Some electricians, notably Faraday, have propounded a molecular theory of electricity, according to which the electrical states are the result of certain peculiar conditions of the molecules of the surfaces that have been rubbed. Another view is to regard the state of electrification as related to the *ether* (the highly-attenuated medium which fills all space, and is the vehicle by which light is transmitted), which is known to be associated with the molecules of matter. Some indeed hold that the ether itself is electricity; and that the two states of positive and negative electrification are simply due to displacement of the ether at the surfaces of bodies. In these lessons we shall avoid as

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tively electrified surface and just within the negatively electrified surface, as though one had a surplus and the other a deficit of electricity. In Fig. 8 lines are drawn across the intervening space from the positively electrified surface to the opposite negative charge. The advantages of this last mode are explained in Art. 13.

10. Conductors and Insulators.—The term "conductors," used above, is applied to those bodies which readily allow electricity to flow through them. Roughly speaking, bodies may be divided into two classes—those which conduct and those which do not; though very many substances are partial conductors, and cannot well be classed in either category. All the metals conduct well; the human body conducts, and so does water. On the other hand glass, sealing-wax, silk, shellac, gutta-percha, indiarubber, resin, fatty substances generally, and the air, are **non-conductors**. On this account these substances are used to make supports and handles for electrical apparatus where it is important that the electricity should not leak away; hence they are sometimes called **insulators** or *isolators*. Faraday termed them **dielectrics**. We have remarked above that the name of *non-electrics* was given to those substances which, like the metals, yield no sign of electrification when held in the hand and rubbed. We now know the reason why they show no electrification; for, being good conductors, the electrification flows away as fast as it is generated. The observation of Gilbert that electrical experiments fail in damp weather is also explained by the knowledge that water is a conductor, the film of moisture on the surface of damp bodies causing the electricity produced by friction to leak away as fast as it is generated.

11. Other Electrical Effects.—The production of electricity by friction is attested by other effects than those of attraction and repulsion, which hitherto we have assumed to be the test of the presence of electricity. Otto von Guericke first observed that sparks and flashes

of light could be obtained from highly electrified bodies at the moment when they were discharged. Such sparks are usually accompanied by a snapping sound, suggesting on a small scale the thunder accompanying the lightning spark, as was remarked by Newton and other early observers. Pale flashes of light are also produced by the discharge of electricity through tubes partially exhausted of air by the air-pump. Other effects will be noticed in due course.

12. Other Sources of Electrification.—The student must be reminded that *friction* is by no means the only source of electrification. The other sources, percussion, compression, heat, chemical action, physiological action, contact of metals, etc., will be treated of in Lesson VII. We will simply remark here that friction between two different substances *always* produces electrical separation, no matter what the substances may be. Symmer observed the production of electrification when a silk stocking was drawn over a woollen one, though woollen rubbed upon woollen, or silk rubbed upon silk, produces no electrical effect. If, however, a piece of rough glass be rubbed on a piece of smooth glass, electrification is observed; and indeed the conditions of the surface play a very important part in the production of electrification by friction. In general, of two bodies thus rubbed together, that one becomes negatively electrical whose particles are the more easily removed by friction. Differences of temperature also affect the electrical conditions of bodies, a warm body being usually negative when rubbed on a cold piece of the same substance. The quantity of electrification produced is, however, not proportional to the amount of the actual mechanical friction; hence it appears doubtful whether friction is truly the cause of the electrification. Something certainly happens when the surfaces of two different substances are brought into intimate contact, which has the result that when they are drawn apart they are found (provided at least

one of them is a non-conductor) to have acquired opposite charges of electrification; one surface having apparently taken some electricity from the other. But these opposite charges attract one another and cannot be drawn apart without there being mechanical work done upon the system. The work thus spent is stored up in the act of separating the charged surfaces; and as long as the charges remain separated they constitute a store of potential energy. The so-called frictional electric machines are therefore machines for bringing dissimilar substances into intimate contact, and then drawing apart the particles that have touched one another and become electrical.

If the two bodies that are rubbed together are both good conductors, they will not become strongly electrified, even if held on insulating handles. It is quite likely, however, that the heat produced by friction, as in the bearings of machinery, is due to electric currents generated where the surfaces meet and slip.

13. Electric Field. — Whenever two oppositely charged surfaces are placed near one another they tend to move together, and the space between them is found to be thrown into a peculiar state of stress, as though the medium in between had been stretched. To explore the space between two bodies one of which has been positively and the other negatively electrified, we may use a light pointer (Fig. 9) made of a small piece of very thin paper pierced with a hole through which passes a long thread of glass. It will be found that this pointer tends to point across from the positively electrified surface to the negatively electrified surface, along invisible *lines of electric force*. The space so filled with electric lines of force is called an *electric field*. In Fig. 8 A and B represent two bodies the surfaces of which have been electrified, the one positively, the other negatively. In

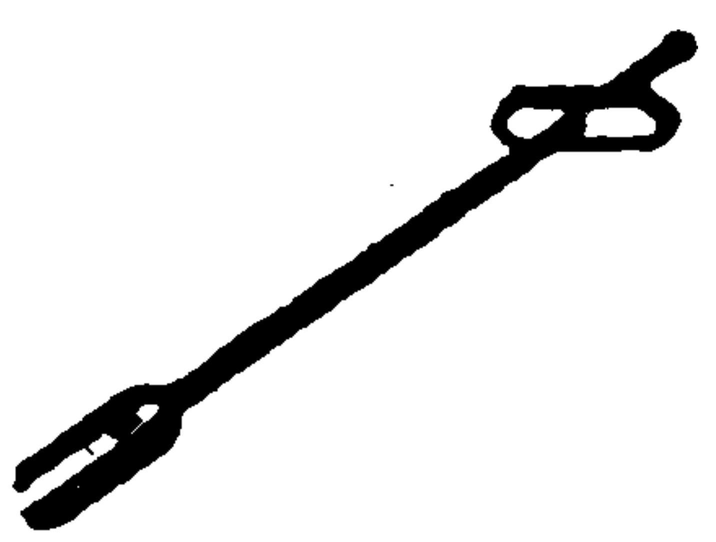


Fig. 9.

the field between them the electric lines pass across almost straight, except near the edges, where they are curved. Electric lines of force start from a positively charged surface at one end, and end on a negatively charged surface at the other end. They never meet or cross one another. Their direction indicates that of the resultant electric force at every point through which they pass. The stress in the medium thus mapped out by the lines of force acts as a tension along them, as though they tended to

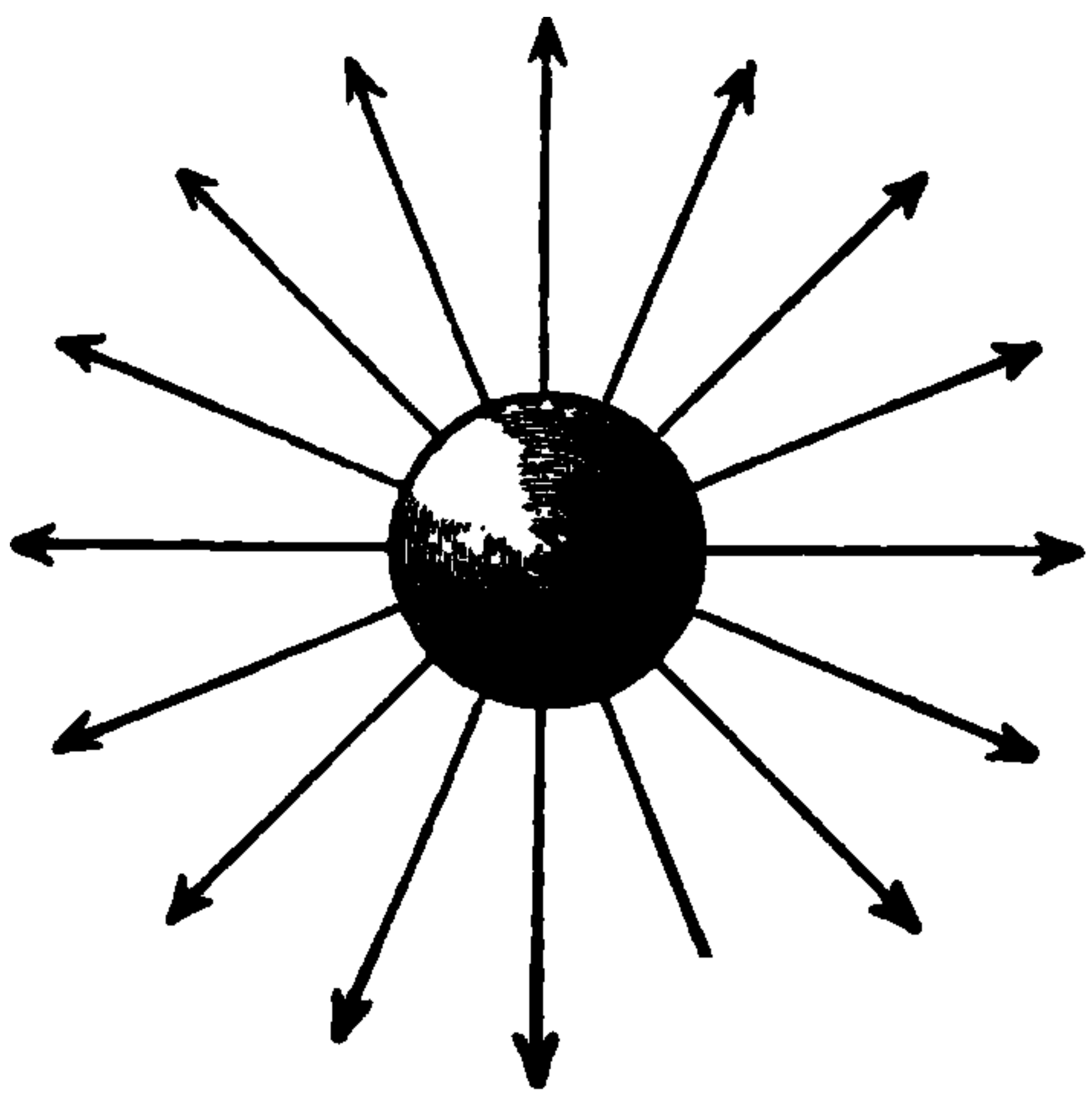


Fig. 10.

shorten themselves. In fact in Fig. 8 the tension in the medium draws the two surfaces together. There is also a pressure in the medium at right angles to the lines, tending to widen the distance between them. Fig. 10 represents a ball which has been positively electrified, and placed at a distance from other objects; the lines in the field being simply radial.

LESSON II. — *Electroscopes*

14. Simple Electroscopes. — An instrument for detecting whether a body is electrified or not, and whether the electrification is positive or negative, is termed an **Electroscope.** The feather which was attracted or repelled, and the two pith-balls which flew apart, as we found in Lesson I., are in reality simple electroscopes. There are, however, a number of pieces of apparatus better adapted for this particular purpose, some of which we will describe.

15. Needle Electroscope. — The earliest electroscope was that devised by Dr. Gilbert, and shown in Fig. 11, which consists of a stiff strip balanced lightly upon a sharp point. A thin strip of brass or wood, a straw, or

even a goose quill, balanced upon a sewing needle, will serve equally well. When an electrified body is held near



Fig. 11.

the electroscope it is attracted and turned round, and will thus indicate the presence of electric charges far too feeble to attract bits of paper from a table.

16. Gold-Leaf Electroscope. — A still more sensi-



Fig. 12.

tive instrument is the **Gold-Leaf Electroscope**, invented by Bennet, and shown in Fig. 12. We have seen how two pith-balls when similarly electrified repel one

the field between them the electric lines pass across almost straight, except near the edges, where they are curved. Electric lines of force start from a positively charged surface at one end, and end on a negatively charged surface at the other end. They never meet or cross one another. Their direction indicates that of the resultant electric force at every point through which they pass. The stress in the medium thus mapped out by the lines of force acts as a tension along them, as though they tended to shorten themselves. In fact in Fig. 8 the tension in the medium draws the two surfaces together. There is also a pressure in the medium at right angles to the lines, tending to widen the distance between them. Fig. 10 represents a ball which has been positively electrified, and placed at a distance from other objects; the lines in the field being simply radial.

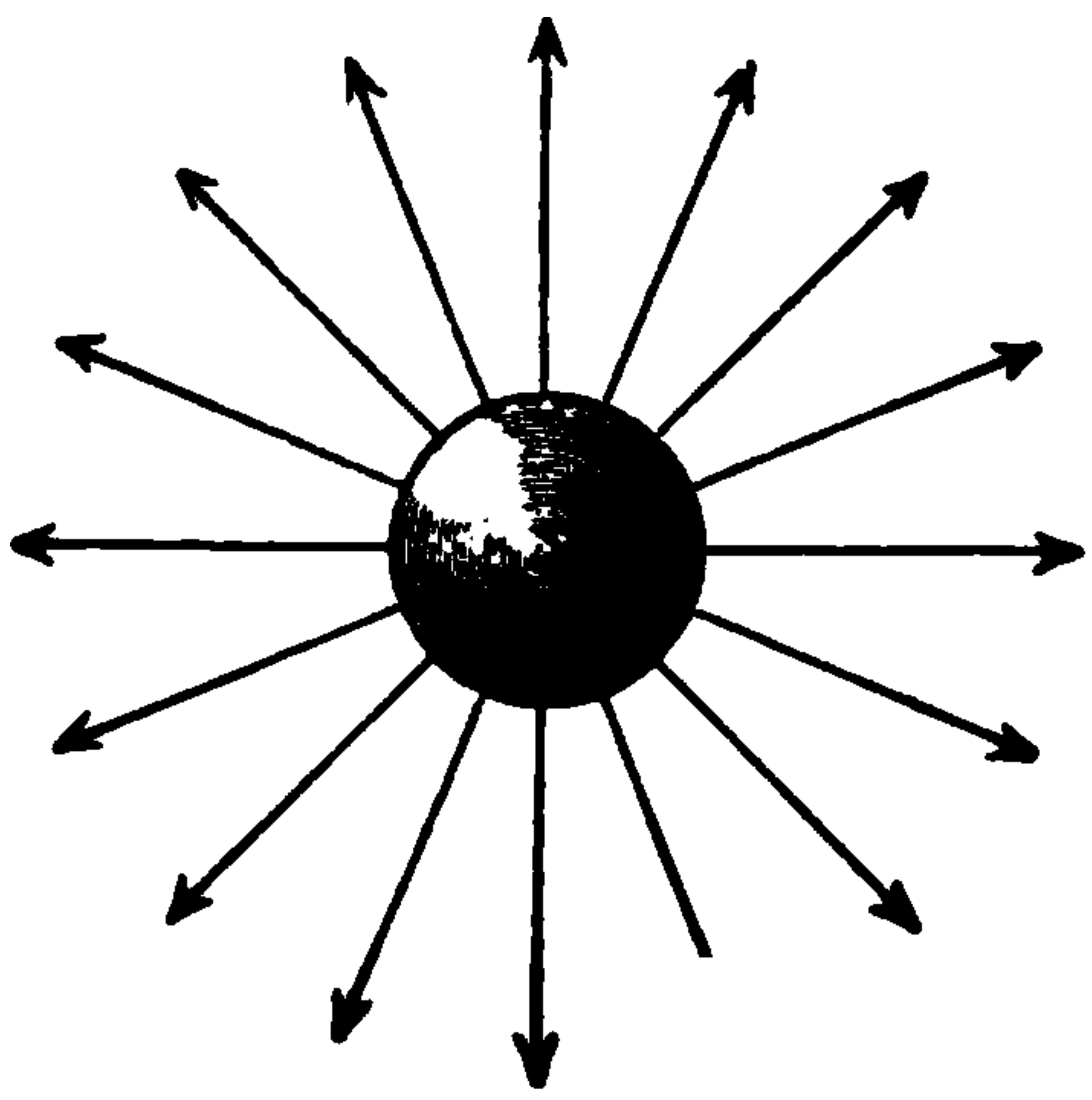


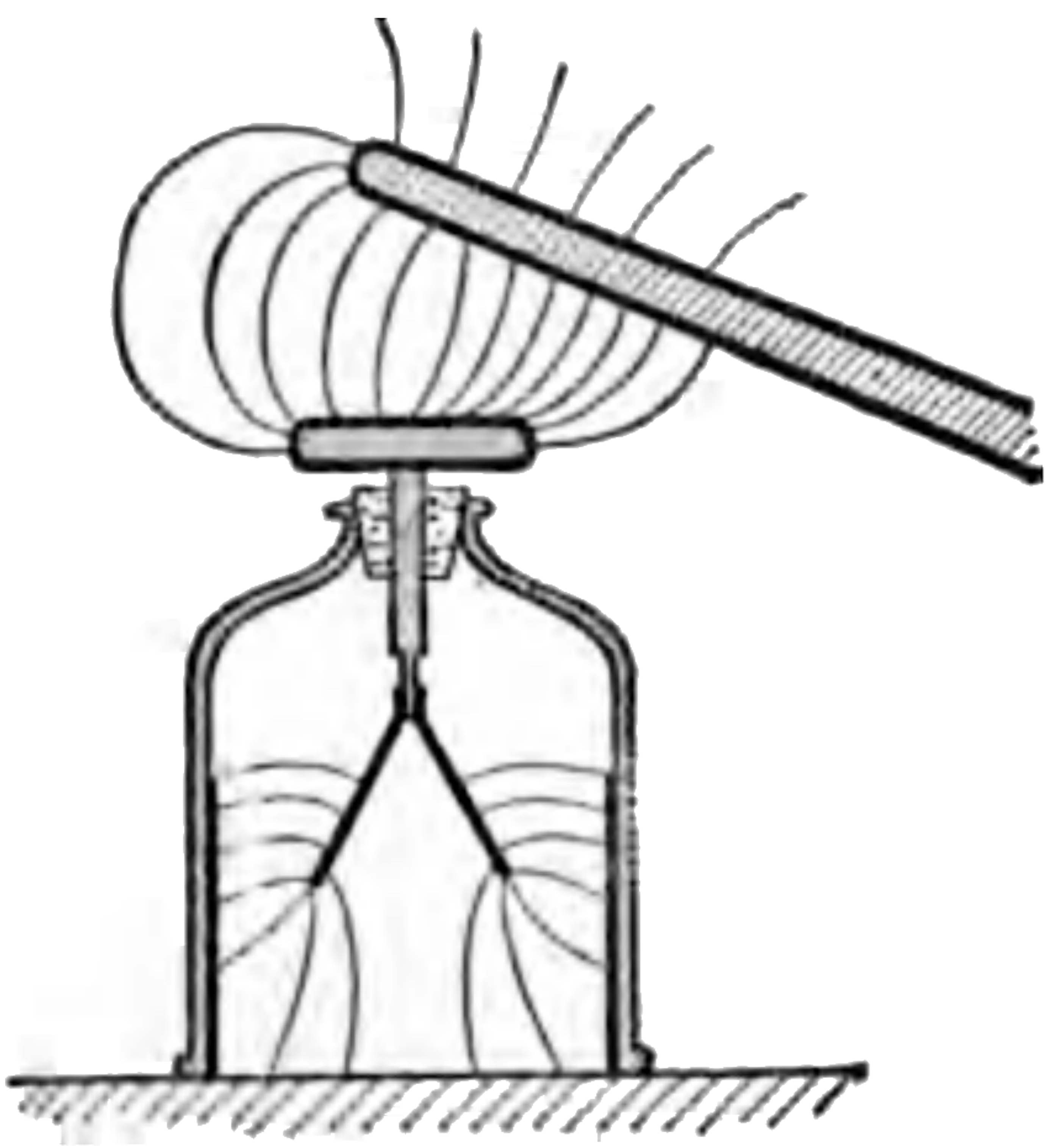
Fig. 10.

Lesson II. — *Electroscopes*

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15. Needle Electroscope. — The earliest electroscope was that devised by Dr. Gilbert, and shown in Fig. 11, which consists of a stiff strip balanced lightly upon a sharp point. A thin strip of brass or wood, a straw, or

proceed as follows:—First charge the gold leaves of the electroscope by touching the knob with a glass rod rubbed on silk. The leaves diverge, being electrified with + electrification. When they are thus charged the approach of a body which is positively electrified will cause them to diverge still more widely; while, on the approach of one negatively electrified, they will tend to close together. If now the brown paper be brought near the electroscope, the leaves will be seen to diverge more, proving the electrification of the paper to be of the same kind as that with which the electroscope is charged, or positive.


Fig. 13

Sometimes the outer surface of the glass jar containing the gold leaves is covered with wire gauze or strips of foil to shield the leaves from the influence of external bodies. A preferable way is to use glass of a kind that conducts.

The part played by the surrounding medium in the operation of the electroscope is illustrated by Fig. 13. Of the electric lines in the field surrounding the rubbed rod a number will pass into the metal cap of the electroscope and emerge below through the leaves. The nearer the rod is brought, the greater will be the number of electric lines thus affecting the instrument. There being a tension along the lines and a pressure across them, the effect is to draw the gold leaves apart as though they repelled each other.

The Gold-Leaf Electroscope will also indicate roughly the amount of electrification on a body placed in contact with it, for the gold leaves open out more widely when the charge thus imparted to them is greater. For exact measurement, however, of the degree of electrification,

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or lever of shellac suspended within a cylindrical glass case by means of a fine silver wire. At one end this lever is furnished with a gilt pith-ball *n*. The upper end of the silver wire is fastened to a brass top, upon which a circle, divided into degrees, is cut. This top can be turned round in the tube which supports it, and is called the torsion-head. Through an aperture in the cover there can be introduced a second gilt pith-ball *m*, fixed to the end of a vertical glass rod *a*. Round the glass case, at the level of the pith-balls, a circle is drawn, and divided also into degrees.



Fig. 15.

In using the torsion balance to measure the amount of a charge of electricity, the following method is adopted:—First, the torsion-head is turned round until the two pith-balls *m* and *n* just touch one another. Then the glass rod *a* is taken out, and the charge of electricity to be measured is imparted to the ball *m*, which is then replaced in the balance. As soon as *m* and *n* touch one another, part of the charge passes from *m* to *n*, and they repel one another because they are then similarly electrified. The ball *n*, therefore, is driven round and twists the wire up to a certain extent. The force of repulsion becomes less and less as *n* gets farther and farther from *m*: but the force of the twist gets greater and greater the more the wire is twisted. Hence these two forces will balance one another when the balls are separated by a certain distance, and it is clear that a large charge of electricity will repel the ball *n* with a greater force than a lesser charge would. The

distance through which the ball is repelled is read off in angular degrees of the scale. When a wire is twisted, the force with which it tends to untwist is precisely proportional to the amount of the twist. The force required to twist the wire ten degrees is just ten times as great as the force required to twist it one degree. In other words, *the force of torsion is proportional to the angle of torsion.* The angular distance between the two balls is, when they are not very widely separated, very nearly proportional to the actual straight distance between them, and represents the force exerted between electrified balls *at that distance* apart. The student must, however, carefully distinguish between the measurement of the force and the measurement of the actual quantity of electricity with which the instrument is charged. For the force exerted between the electrified balls will vary at different distances according to a particular law known as the "law of inverse squares," which requires to be carefully explained.

19. The Law of Inverse Squares. — Coulomb proved, by means of the Torsion Balance, that the force exerted between two small electrified bodies varies inversely as the square of the distance between them when the distance is varied. Thus, suppose two small electrified bodies 1 inch apart repel one another with a certain force, at a distance of 2 inches the force will be found to be only one quarter as great as the force at 1 inch; and at 10 inches it will be only $\frac{1}{100}$ part as great as at 1 inch. This law is proved by the following experiment with the torsion balance. The two scales were adjusted to 0°, and a certain charge was then imparted to the balls. The ball *n* was repelled round to a distance of 36°. The twist on the wire between its upper and lower ends was also 36°, or the force tending to repel was thirty-six times as great as the force required to twist the wire by 1°. The torsion-head was now turned round so as to twist the thread at the top and force

the ball n nearer to m, and was turned round until the distance between n and m was halved. To bring down this distance from 36° to 18°, it was found needful to twist the torsion-head through 126°. The total twist between the upper and lower ends of the wire was now 126° + 18°, or 144°; and the force was 144 times as great as that force which would twist the wire 1°. But 144 is four times as great as 36; hence we see that while the distance had been reduced to one *half*, the force between the balls had become *four times* as great. Had we reduced the distance to *one quarter*, or 9°, the total torsion would have been found to be 576°, or *sixteen* times as great; proving **the force to vary inversely as the square of the distance.**

In practice it requires great experience and skill to obtain results as exact as this, for there are many sources of inaccuracy in the instrument. The balls must be very small, in proportion to the distances between them. The charges of electricity on the balls are found, moreover, to become gradually less and less, as if the electricity leaked away into the air. This loss is less if the apparatus be quite dry. It is therefore usual to dry the interior by placing inside the case a cup containing either chloride of calcium, or pumice stone soaked with strong sulphuric acid, to absorb the moisture.

Before leaving the subject of electric forces, it may be well to mention that the force of *attraction* between two oppositely electrified bodies varies also inversely as the square of the distance between them. And in every case, whether of attraction or repulsion, the force at any given distance is **proportional to the product of the two quantities of electricity** on the bodies. Thus, if we had separately given a charge of 2 to the ball m and a charge of 3 to the ball n, the force between them will be $3 \times 2 = 6$ times as great as if each had had a charge of 1 given to it. It must be remembered, however, that the

law of inverse squares is only true when applied to the case of bodies so small, as compared with the distance between them, that they are mere points. For flat, large, or elongated bodies the law of inverse squares does not hold good. The attraction between two large flat disks oppositely electrified with given charges, and placed near together, does not vary with the distance.

20. Field between two Balls. — The electric field (Art. 13) between two oppositely electrified balls is found to consist of curved lines. By the principle laid down in Art. 13, there is a tension along these lines so that they tend not only to draw the two balls together, but also to draw the electrifications on the surfaces of the balls toward one another.

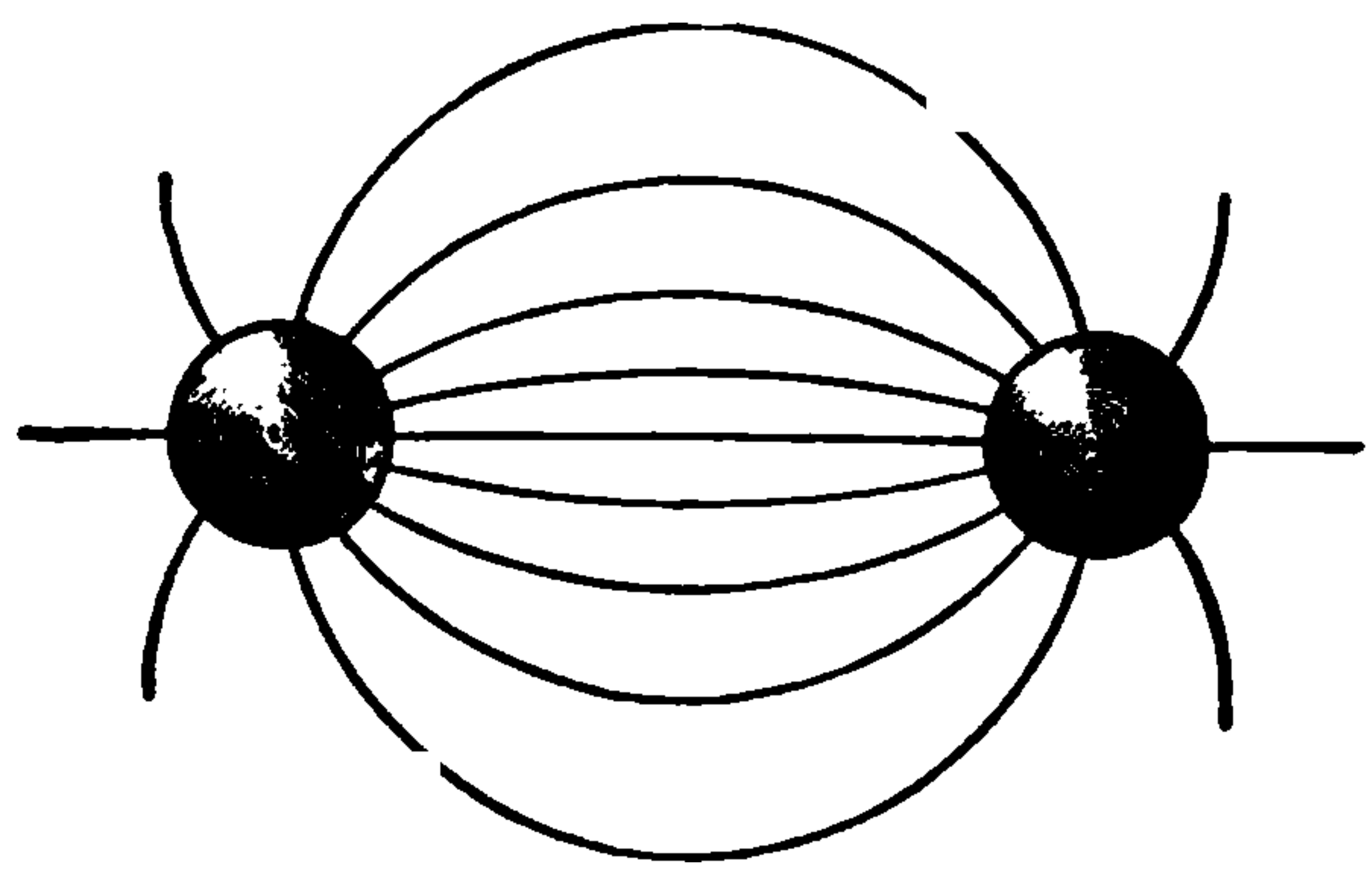


Fig. 16.

There is also a lateral pressure in the medium tending to keep the electric lines apart from one another. One result of these actions is that the charges are no longer equally distributed over the surfaces, but are more dense on the parts that approach most nearly.

21. Unit Quantity of Electricity. — In consequence of these laws of attraction and repulsion, it is found most convenient to adopt the following definition for that quantity of electricity which we take for a unit or standard by which to measure other quantities of electricity. *One (electrostatic) Unit of Electricity is that quantity which, when placed at a distance of one centimetre in air from a similar and equal quantity, repels it with a force of one dyne.* If instead of air another medium occupies the space, the force will be different. For example, if petroleum is used the force exerted between given charges will be about half as great (see Art. 56). Further information about the measurement of electrical quantities is given in Lessons XXI. and XXII.

Lesson III. — *Electrification by Influence*

22. Influence. — We have now learned how two charged bodies may apparently attract or repel one another. It is sometimes said that it is the charges in the bodies which attract or repel one another; but as electrification is not known to exist except in or on material bodies, the proof that it is the charges themselves which are acted upon is only indirect. Nevertheless there are certain matters which support this view, one of

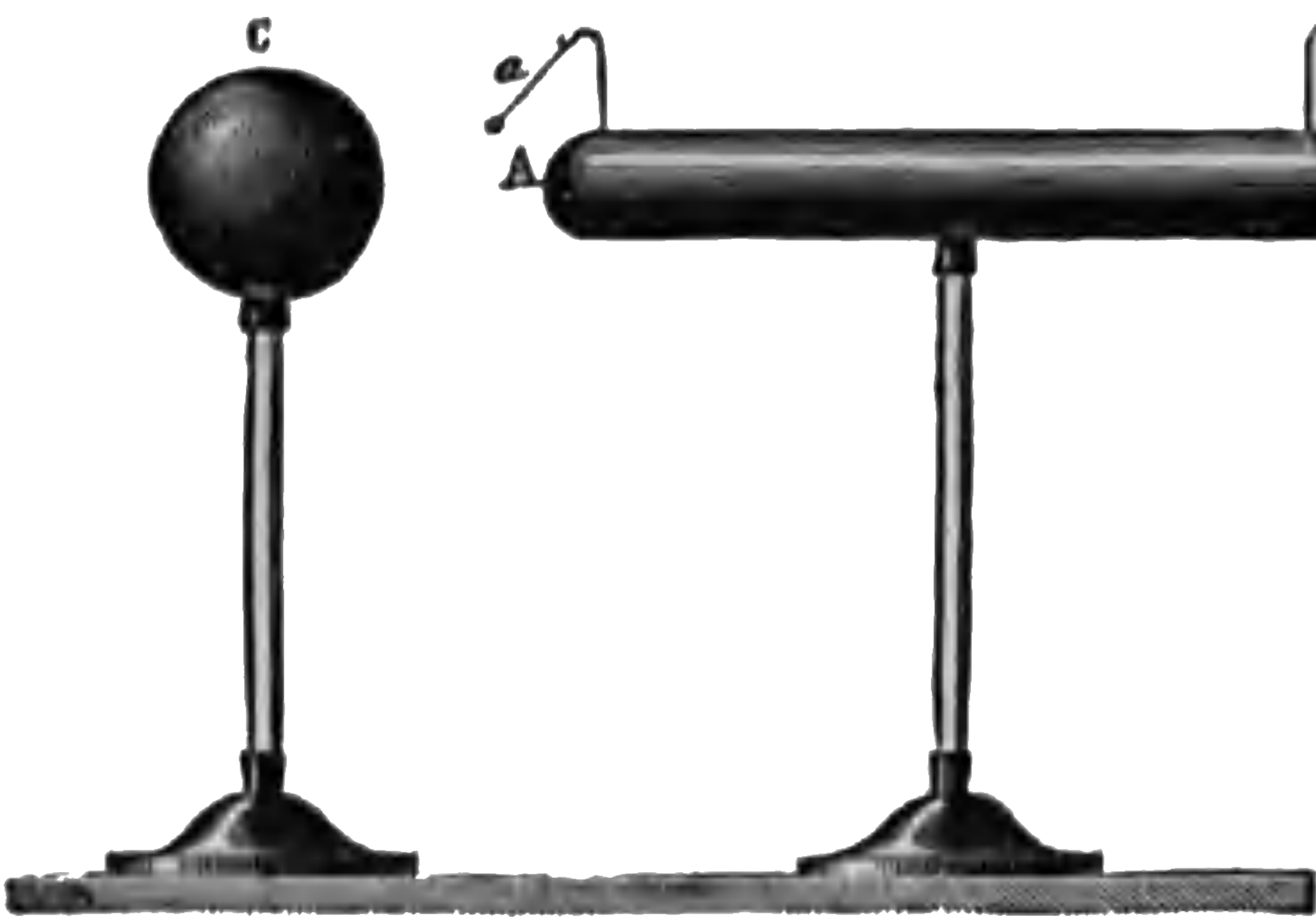


Fig. 17.

these being the electric influence exerted by an electrified body upon one not electrified.

Suppose we electrify positively a ball C, shown in Fig. 17, and hold it near to a body that has not been electrified, what will occur? We take for this experiment the apparatus shown on the right, consisting of a long sausage-shaped piece of metal, either hollow or solid, held upon a glass support. This "conductor," so called because it is made of metal which permits electricity to pass freely through it or over its surface, is supported on glass to

prevent the escape of electricity to the earth, glass being a non-conductor. The influence of the positive charge of the ball placed near this conductor is found to *induce* electrification on the conductor, which, although it has not been rubbed itself, will be found to behave at its two ends as an electrified body. The ends of the conductor will attract little bits of paper; and if pith-balls be hung to the ends they are found to be repelled. It will, however, be found that the middle region of the long-shaped conductor will give no sign of any electrification. Further examination will show that the two electrifications on the ends of the conductor are of opposite kinds, that nearest the excited glass ball being a negative charge, and that at the farthest end being an equal charge, but of positive sign. It appears then that a positive charge attracts negative and repels positive, and that this influence can be exerted at a distance from a body. If we had begun with a charge of negative electrification upon a stick of sealing-wax, the presence of the negative charge near the conductor would have induced a positive charge on the near end, and negative on the far end. This action, discovered in 1753 by John Canton, is spoken of as **influence** or **electrostatic induction.*** It will take place across a considerable distance. Even if a large sheet of glass be placed between, the same effect will be produced. When the electrified body is removed both the charges disappear and leave no trace behind, and the glass ball is found to be just as much electrified as before; it has parted with none of its own charge. It

* The word *induction* originally used was intended to denote an action at a distance, as distinguished from *conduction*, which implied the conveyance of the action by a material conductor. But there were discovered other actions at a distance, namely, the induction of currents by moving magnets, or by other currents, and the induction of magnetism in iron in the presence of a neighbouring magnet. As the term *induction* has now been officially adopted for the induction of currents, its use in other senses ought to be dropped. Hence the preference now given to the term *influence* for the induction of charges by charges.

will be remembered that on one theory a body charged positively is regarded as having *more* electricity than the things round it, while one with a negative charge is regarded as having *less*. According to this view it would appear that when a body (such as the + electrified glass ball) having more electricity than things around it is placed near an insulated conductor, the uniform distribution of electricity in that conductor is disturbed, the electricity flowing away from that end which is near the + body, leaving less than usual at that end, and producing more than usual at the other end. This view of things will account for the disappearance of all signs of electrification when the electrified body is removed, for then the conductor returns to its former condition; and being neither more nor less electrified than all the objects around on the surface of the earth, will show neither positive nor negative charge.

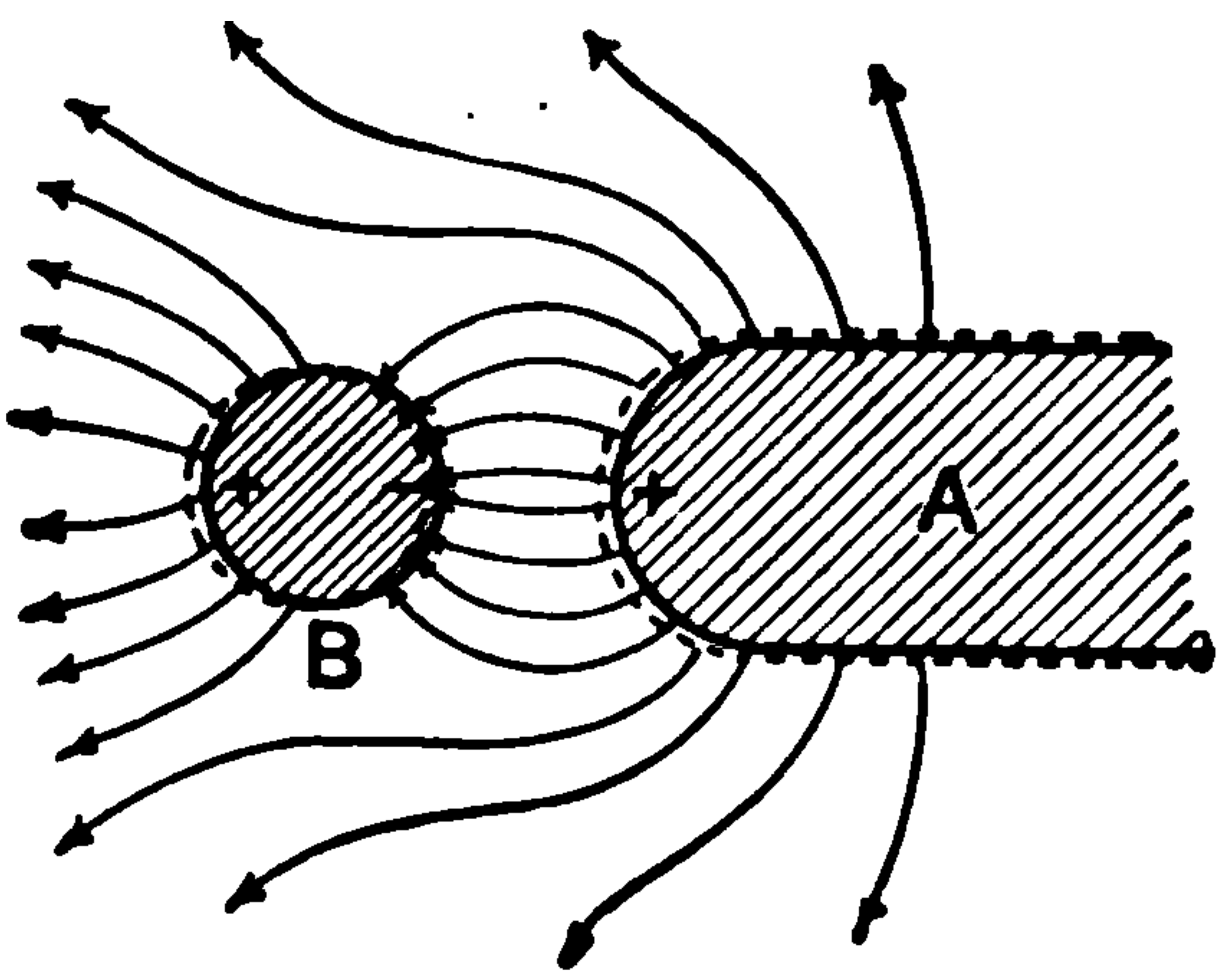


Fig. 18.

The action is not, however, a mere action at a distance; it is one in which the intervening medium takes an essential part. Consider (Fig. 18) what takes place when an insulated, non-electrified metal ball B is brought under the influence of a positively electrified body A. At once some of the electric lines of the field that surrounds A pass through B, entering it at the side nearer A, and leaving it at the farther side. As the ball B has no charge of its own, as many electric lines will enter on one side as leave on the other; or, in other words, the induced negative charge on one side and the induced positive charge on the other will be exactly equal in amount. They will not, however, be quite equally distributed, the negative charge on the side nearer A being more concentrated, and the lines in the field on that side denser.

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another, leaving the induced charge of positive electricity, which was formerly repelled to the other end of the conductor, as a permanent charge after the electrified body has been removed.

In Fig. 19 is illustrated the operation of gradually lowering down over a table a positively electrified metal ball. The nearer it approaches the table, the more does the electric field surrounding it concentrate itself in the gap between the ball and the table top; the latter becoming negatively electrified by influence. Where the electric lines are densest the tension in the medium is greatest, until when the ball is lowered still further the mechanical resistance of the air can no longer withstand the stress; it breaks down and the layer of air is pierced by a spark. If oil is used as a surrounding medium instead of air, it will be found to stand a much greater stress without being pierced.

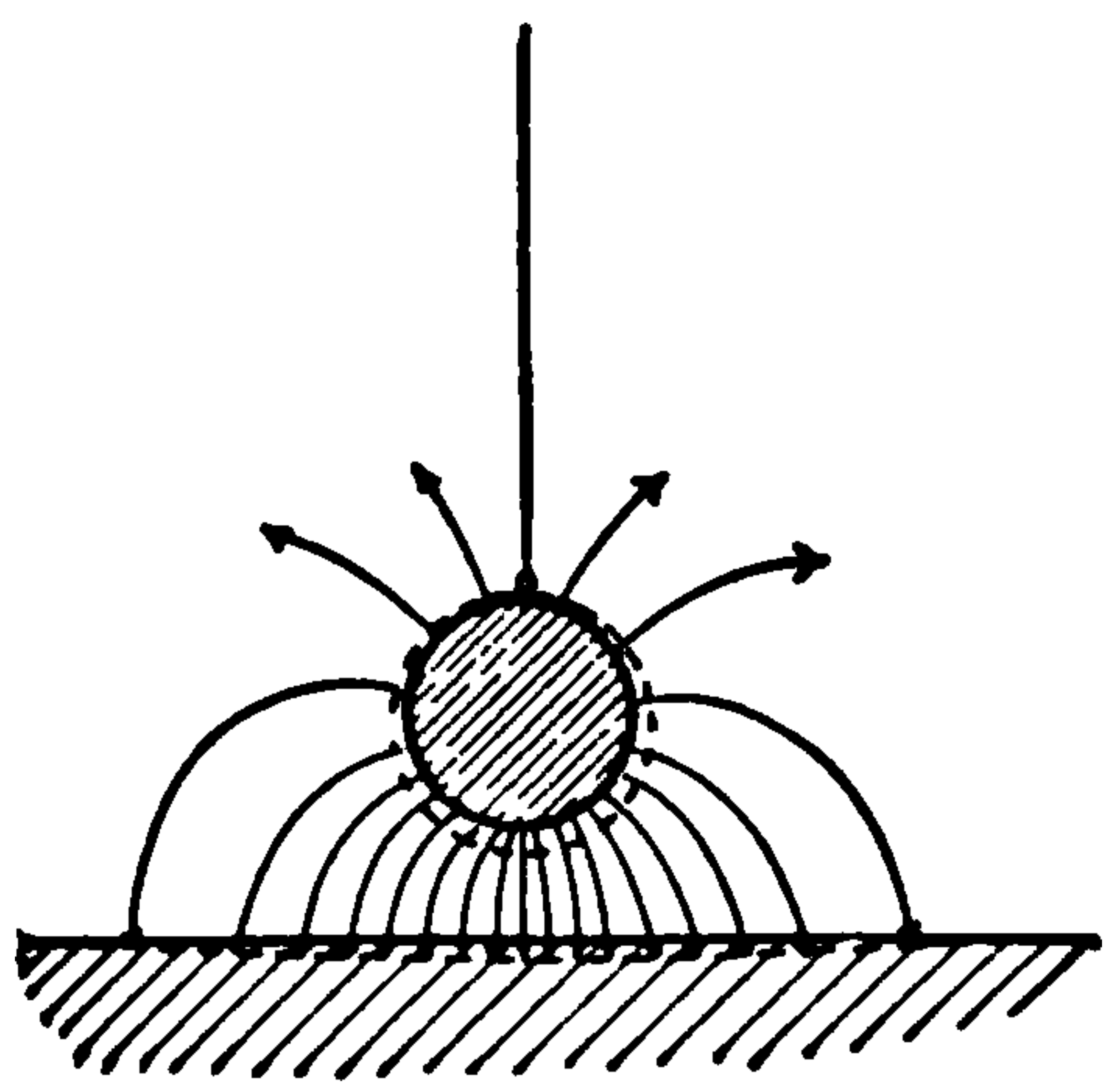


Fig. 19.

24. Attraction due to Influence. — We are now able to apply the principle of influence to explain why an electrified body should attract things that have not been electrified at all. Fig. 18, on p. 26, may be taken to represent a light metal ball B hung from a silk thread presented to the end of a rubbed glass rod A. The positive charge on A produces *by influence* a negative charge on the nearer side of B and an equal positive charge on the far side of B. The nearer half of the ball will therefore be attracted, and the farther half repelled; but the attraction will be stronger than the repulsion, because the attracted charge is nearer than the repelled. Hence on the whole the ball will be attracted. It can easily be observed that if a ball of non-conducting substance, such as wax, be employed, it is not attracted

so much as a ball of conducting material. This in itself *proves* that influence really precedes attraction.

Another way of stating the facts is as follows:—The tension along the electric field on the right of B will be greater than that on the left, because of the greater concentration of the electric lines on the right.

25. Dielectric Power.—We have pointed out several times what part the intervening medium plays in these actions at a distance. The air, oil, glass, or other material between does not act simply as a non-conductor; it takes part in the propagation of the electric forces. Hence Faraday, who discovered this fact, termed such materials *dielectrics*. Had oil, or solid sulphur, or glass been used instead of air, the influence exerted by the presence of the electrified body at the same distance would have been greater. The power of a non-conducting substance to convey the influence of an electrified body across it is called its *dielectric power* (or was formerly called its specific *inductive capacity*, see Art. 56 and Lesson XXIII.).

26. The Electrophorus.—We are now prepared to explain the operation of a simple and ingenious instrument, devised by Volta in 1775, for the purpose of procuring, by the principle of influence, an unlimited number of charges of electricity from one single charge. This instrument* is the **Electrophorus** (Fig. 20). It consists of two parts, a round cake of resinous material cast in a metal dish or "sole," about 12 inches in diameter, and a round disk of slightly smaller diameter made of metal, or of wood covered with tinfoil, and provided with a glass handle. Shellac, or sealing-wax, or a mixture of resin, shellac, and Venice turpentine, may be used to make the cake. A slab of sulphur will also answer, but it is liable to crack. Sheets of hard ebonized indiarubber are excellent; but the surface of this substance

* Volta's electrophorus was announced in 1775. Its principle had already been anticipated by Wilcke, who in 1762 described to the Swedish Academy of Sciences two "charging-machines" working by influence.

requires occasional washing with ammonia and rubbing with paraffin oil, as the sulphur contained in it is liable to oxidize and to attract moisture. To use the electrophorus the resinous cake must be beaten or rubbed with a warm piece of woollen cloth, or, better still, with a cat's



Fig. 20.

skin. The disk or "cover" is then placed upon the cake, touched momentarily with the finger, then removed by taking it up by the glass handle, when it is found to be powerfully electrified with a positive charge, so much so indeed as to yield a spark when the knuckle is presented to it. The "cover" may be replaced, touched, and once more removed, and will thus yield any number of sparks,

the original charge on the resinous plate meanwhile remaining practically as strong as before.

The theory of the electrophorus is very simple, provided the student has clearly grasped the principle of influence explained above. When the resinous cake is first beaten with the cat's skin its surface is negatively electrified, as indicated in Fig. 21. When the metal disk is placed down upon it, it rests really only on three or four points of the surface, and may be regarded as an insulated conductor in the presence of an electrified body. The negative electrification of the cake therefore acts by influence on the metallic disk or "cover," the natural electricity in it being displaced downwards, producing a positive charge on the under side, and leaving the upper



Fig. 21.

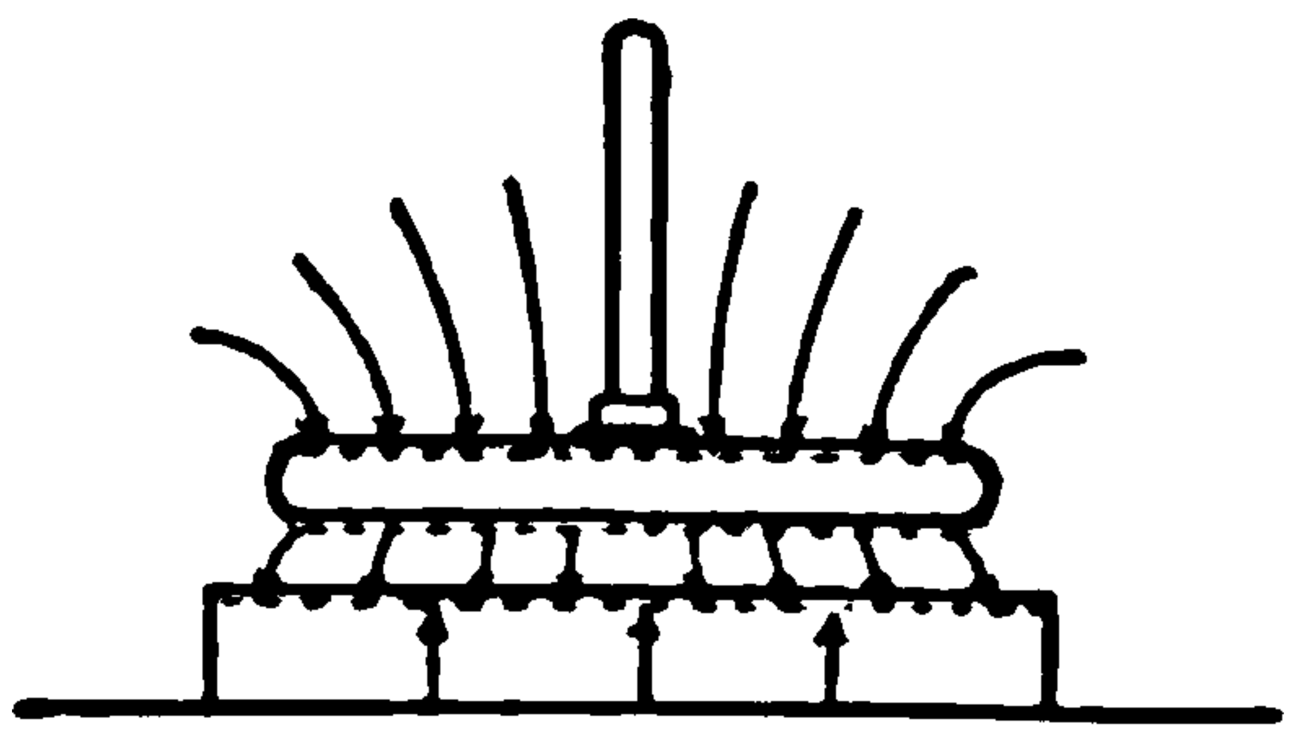


Fig. 22.

side negatively electrified. This state of things is shown in Fig. 22. If now the cover be touched for an instant with the finger, the negative charge of the upper surface will be neutralized by electricity flowing in from the earth through the hand and body of the experimenter. The attracted positive charge will, however, remain, being bound as it were by its attraction towards the negative charge on the cake. Fig. 23 shows the condition of things after the cover has been touched. If, finally, the cover be lifted by its handle, the remaining positive charge will be no longer "bound" on the lower surface by attraction, but will distribute itself on both sides of the cover, and may be used to give a spark, as already said. It is clear that no part of the original charge has been consumed in the process, which may be repeated as

often as desired. As a matter of fact, the charge on the cake slowly dissipates — especially if the air be damp. Hence it is needful sometimes to renew the original charge by afresh beating the cake with the cat's skin. The labour of touching the cover with the finger at each operation may be saved by having a pin of brass or a strip of tinfoil projecting from the metallic "sole" on to the top of the cake, so that it touches the plate each time, and thus neutralizes the negative charge by allowing electricity to flow in from the earth.

The principle of the electrophorus may then be summed up in the following sentence. *A conductor if*

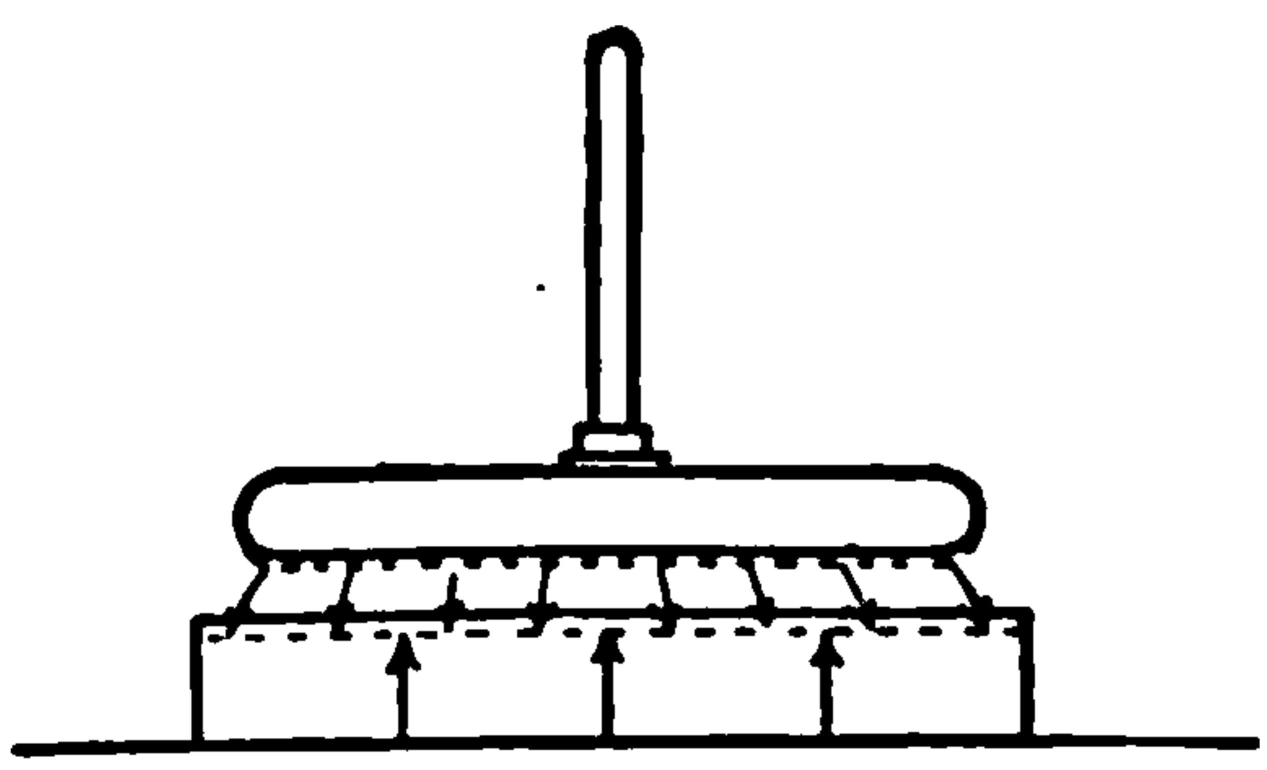


Fig. 23.

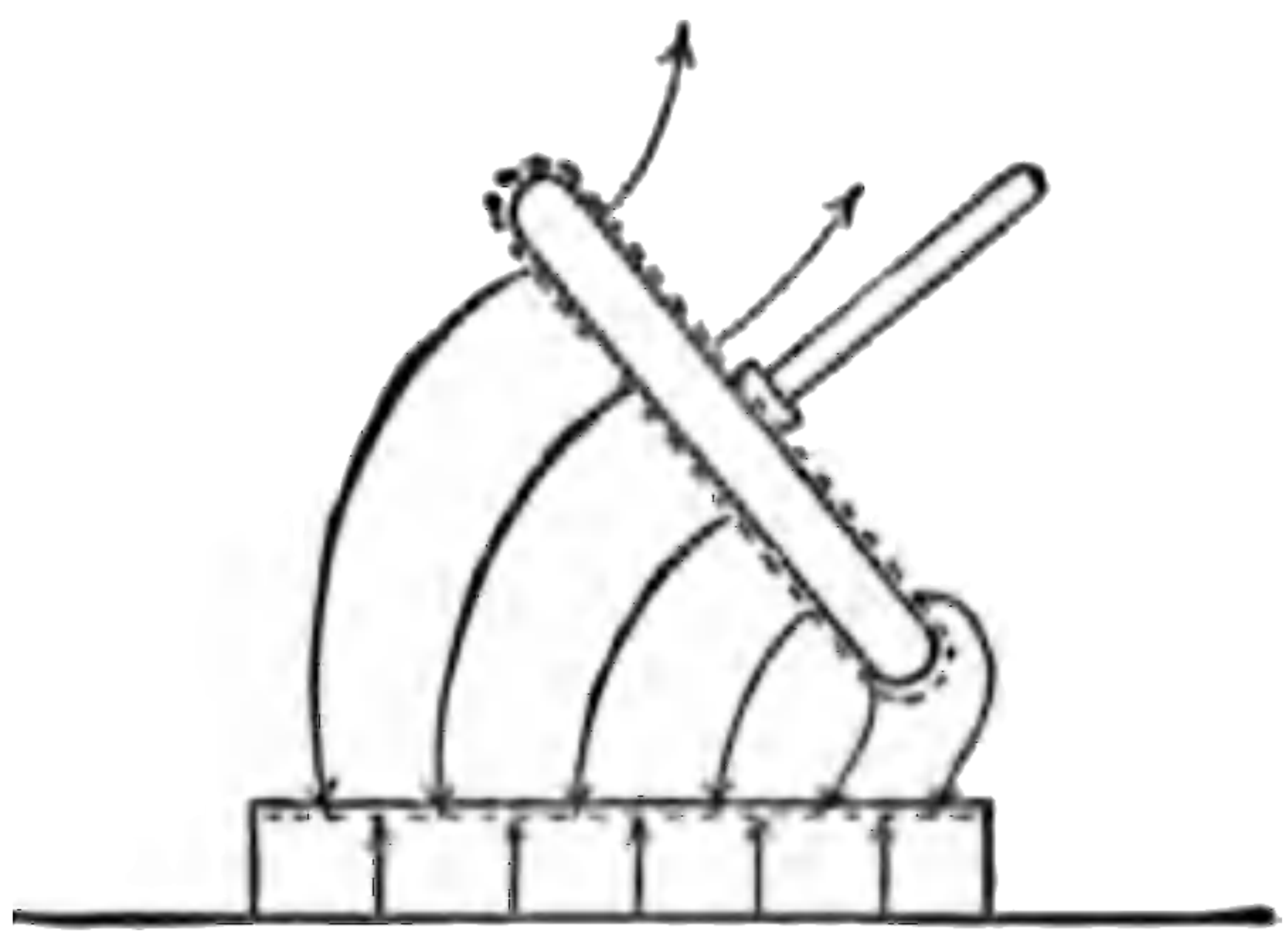


Fig. 24.

*touched while under the influence of a charged body acquires thereby a charge of opposite sign.**

Since the electricity thus yielded by the electrophorus is not obtained at the expense of any part of the original charge, it is a matter of some interest to inquire what the source is from which the energy of this apparently unlimited supply is drawn; for it cannot be called into

* Priestley, in 1767, stated this principle in the following language:— "The electric fluid, when there is a redundancy of it in any body, repels the electric fluid in any other body, when they are brought within the sphere of each other's *influence*, and drives it into the remote parts of the body; or quite out of the body, if there be any outlet for that purpose. In other words, bodies immerged in electric atmospheres always become possessed of the electricity, contrary to that of the body, in whose atmosphere they are immerged."

existence without the expenditure of some other form of energy, any more than a steam-engine can work without fuel. As a matter of fact it is found that it is a little harder work to lift up the cover when it is charged than if it were not charged; for, when charged, there is the tension of the electric field to be overcome as well as the force of gravity. Slightly harder work is done at the expense of the muscular energies of the operator; and this is the real origin of the energy stored up in the separate charges. The purely mechanical actions of putting down the disk on the cake, touching it, and lifting it up, can be performed automatically by suitable mechanical arrangements, which render the production of these inductive charges practically continuous. Of such continuous electrophori, the latest is Wimshurst's machine, described in Lesson V.

27. "Free" and "Bound" Electrification.—We have spoken of a charge of electricity on the surface of a conductor, as being "bound" when it is attracted by the presence of a neighbouring charge of the opposite kind. The converse term "free" is sometimes applied to the ordinary state of electricity upon a charged conductor, not in the presence of a charge of an opposite kind. A "free" charge upon an insulated conductor flows away instantaneously to the earth, if a conducting channel be provided, as will be explained. It is immaterial what point of the conductor be touched. Thus, in the case represented in Fig. 17, wherein a + electrified body induces – electrification at the near end, and + electrification at the far end of an insulated conductor, the – charge is "bound," being attracted, while the + charge at the other end, being repelled, is "free"; and if the insulated conductor be touched by a person standing on the ground, the "free" charge will flow away through his body to the earth, or to the walls of the room, while the "bound" charge will remain, no matter whether he touch the conductor at the far end, or at the near end, or at the middle.

28. Method of charging the Gold-Leaf Electroscope by Influence.—The student will now be prepared to understand the method by which a Gold-Leaf Electroscope can be charged with the opposite kind of charge to that of the electrified body used to charge it. In Lesson II. it was assumed that the way to charge an electroscope was to place the excited body in contact with the knob, and thus permit, as it were, a small portion of the charge to flow into the gold leaves. A rod of glass rubbed on silk being + would thus obviously impart + electrification to the gold leaves.

Suppose, however, the rubbed glass rod to be held a few inches above the knob of the electroscope, as is indeed shown in Fig. 12. Even at this distance the gold leaves diverge, and the effect is due to influence. The gold leaves, and the brass wire and knob, form one continuous conductor, insulated from the ground by the glass jar. The presence of the + charge of the glass acts inductively on this "insulated conductor," inducing − electrification on the near end or knob, and inducing + at the far end, *i.e.* on the gold leaves, which diverge. Of these two induced charges, the − on the knob is "bound," while the + on the leaves is "free." If now, while the excited rod is still held above the electroscope, the knob be touched by a person standing on the ground, one of these two induced charges flows to the ground, namely, the free charge—not that on the knob itself, for it was "bound," but that on the gold leaves which was "free"—and the gold leaves instantly drop down straight. There now remains only the − charge on the knob, "bound" so long as the + charge of the glass rod is near to attract it. But if, finally, the glass rod be taken right away, the − charge is no longer "bound" on the knob, but is "free" to flow into the leaves, which once more diverge—but this time with a *negative* electrification.

29. The "Return-Shock."—It is sometimes noticed that, when a charged conductor is suddenly discharged,

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classification of bodies into *conductors* and *insulators* has been observed.

This distinction cannot, however, be entirely maintained, as a large class of substances occupy an intermediate ground as partial conductors. For example, dry wood is a bad conductor and also a bad insulator; it is a good enough conductor to conduct away the high-potential electricity obtained by friction, but it is a bad conductor for the relatively low-potential electricity of small voltaic batteries. Substances that are very bad

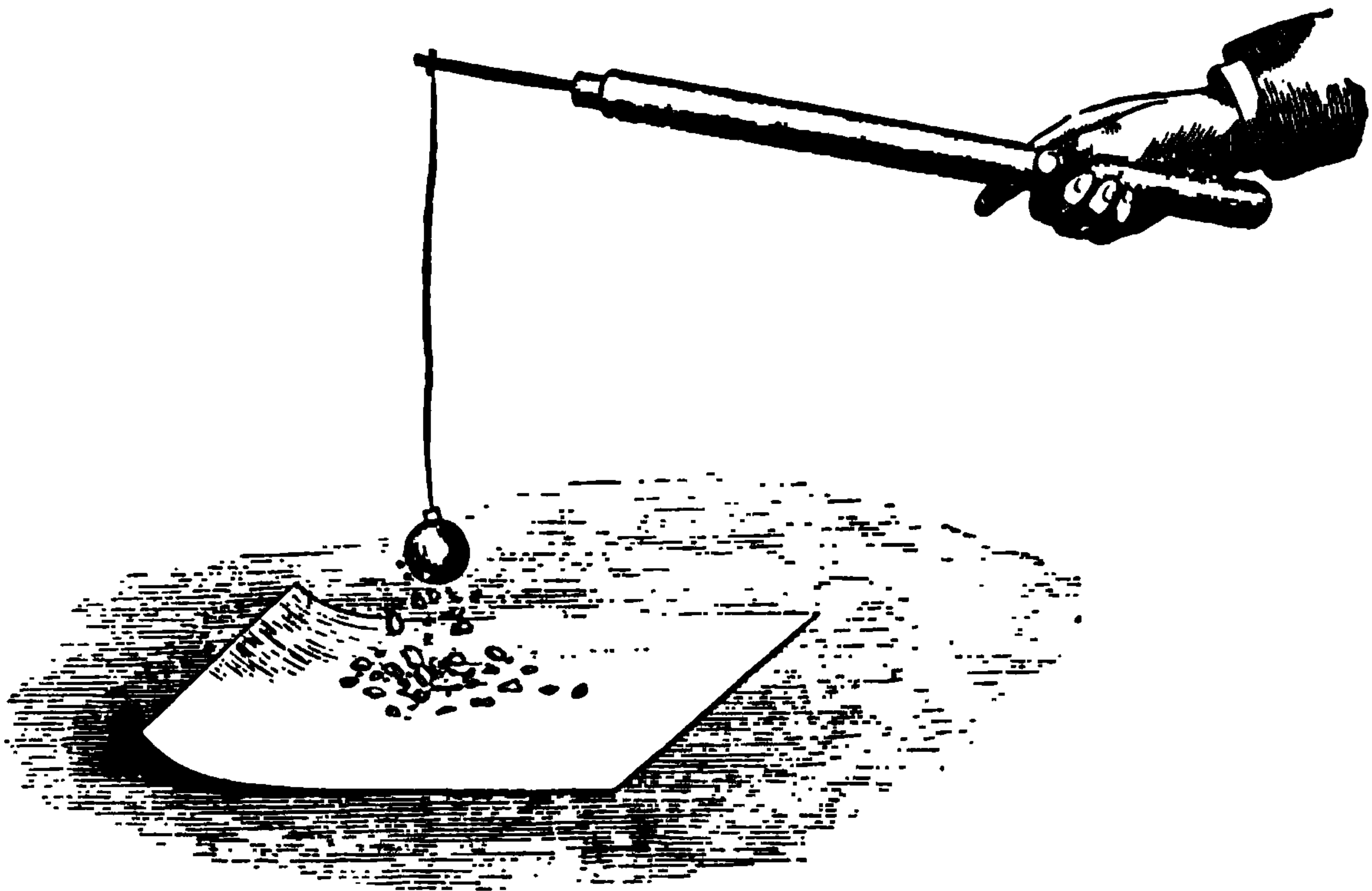


Fig. 25.

conductors are said to offer a great resistance to the flow of electricity through them. There is indeed no substance so good a conductor as to be devoid of resistance. There is no substance of so high a resistance as not to conduct a little. Even silver, which conducts best of all known substances, resists the flow of electricity to a small extent; and, on the other hand, such a non-conducting substance as glass, though its resistance is many million times greater than any metal, does allow a very small quantity of electricity to pass through it. In the

following list, the substances named are placed in order, each conducting better than those lower down on the list.

Substance	Class
Silver	Good Conductors.
Copper	
Other metals	
Charcoal	
Water	
The body	Partial Conductors.
Cotton	
Dry wood	
Marble	
Paper	
Oils	Non-Conductors or Insulators.
Porcelain	
Wool	
Silk	
Resin	
Guttapercha	
Shellac	
Ebonite	
Paraffin	
Glass	
Quartz (fused)	
Air	

A simple way of observing experimentally whether a body is a conductor or not, is to take a charged gold-leaf electroscope, and, holding the substance to be examined in the hand, touch the knob of the electroscope with it. If the substance is a conductor the electricity will flow away through it and through the body to the earth, and the electroscope will be discharged. Through good conductors the rapidity of the flow is so great that the discharge is practically instantaneous. Further information on this question is given in Lesson XXXIII.

31. Distribution of Charge on Bodies. — If electrification is produced at one part of a non-conducting body, it remains at that point and does not flow over the surface, or at most flows over it excessively slowly.

Thus if a glass tube is rubbed at one end, only that one end is electrified. Hot glass is, however, a conductor. If a warm cake of resin be rubbed at one part with a piece of cloth, only the portion rubbed will attract light bodies, as may be proved by dusting upon it through a piece of muslin fine powders such as red lead, lycopodium, or verdigris, which adhere where the surface is electrified. The case is, however, wholly different when a charge of electricity is imparted to any part of a conducting body placed on an insulating support, for it *instantly* distributes itself all over the surface, though in general not uniformly over all points of the surface.

32. The Charge resides on the Surface.— A charge of electricity resides only on the surface of conducting bodies. This is proved by the fact that it is found to be immaterial to the distribution what the interior of a conductor is made of; it may be solid metal, or hollow, or even consist of wood covered with tinfoil or gilt, but, if the shape be the same, the charge will distribute itself precisely in the same manner over the surface. There are also several ways of proving by direct experiment this very important fact. Let a hollow metal ball, having an aperture at the top, be taken (as in Fig. 26), and set upon an insulating stem, and charged by sending into it a few sparks from an electrophorus. The absence of any charge in the interior may be shown as follows:—In order to observe the nature of the electrification of a charged body, it is convenient to have some means of removing a small quantity of the charge as a sample for examination. To obtain such a sample, a little instrument known as a proof-plane is employed. It consists of a little disk of sheet copper or of gilt paper fixed at the end of a small glass rod. If this disk is laid on the surface of an electrified body at any point, part of the charge flows into it, and it may be then removed, and the sample thus obtained may be examined with a gold-leaf electroscope in the ordinary way. For some

purposes a metallic bead, fastened to the end of a glass rod, is more convenient than a flat disk. If such a proof-plane be applied to the outside of our electrified hollow ball, and then touched on the knob of an electroscope, the gold leaves will diverge, showing the presence of a

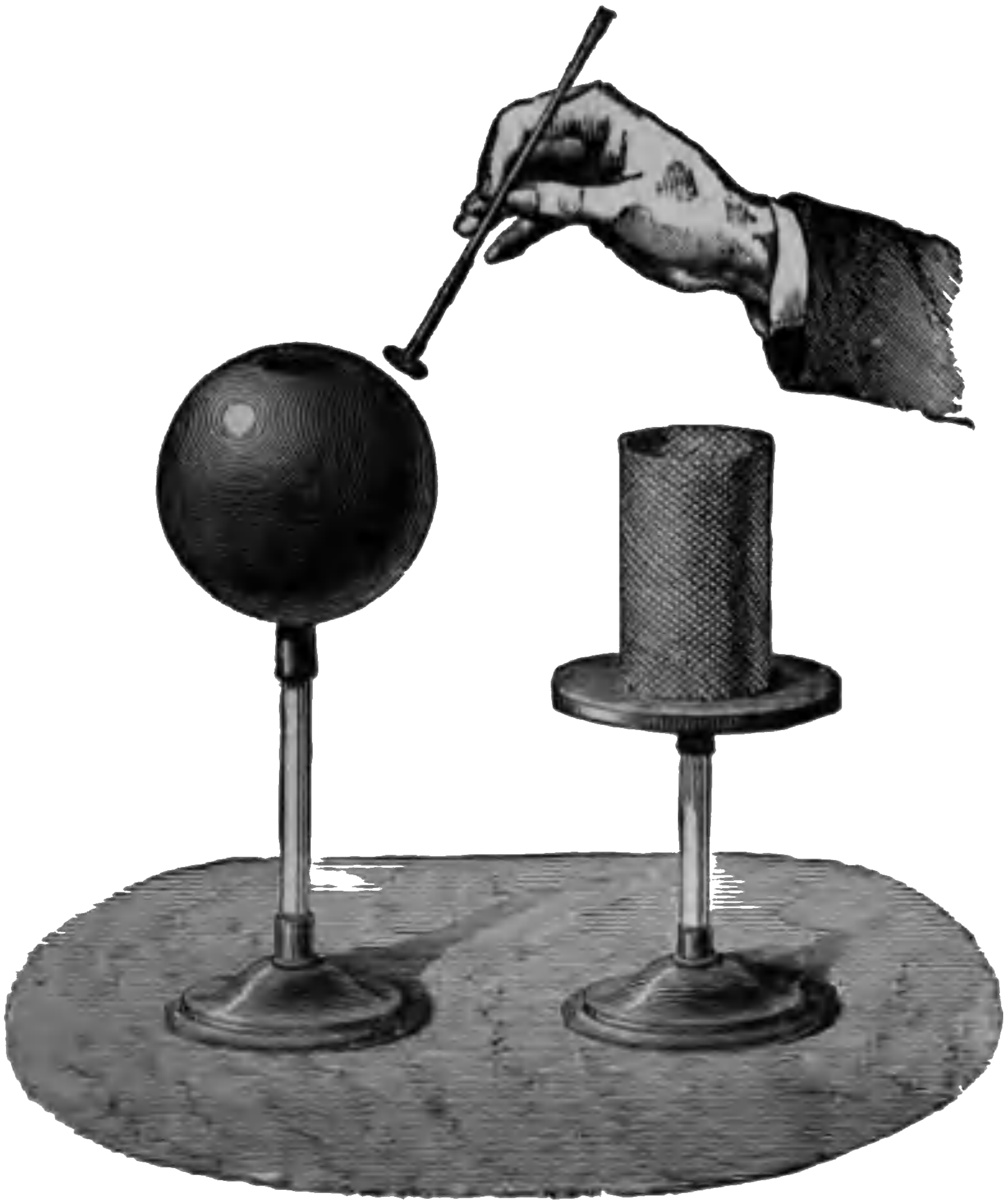


Fig. 26.

charge. But if the proof-plane be carefully inserted through the opening, and touched against the *inside* of the globe and then withdrawn, it will be found that the inside is destitute of electrification. An electrified pewter mug will show a similar result, and so will even a cylinder of gauze wire.

33. Biot's Experiment.— Biot proved the same fact in another way. A copper ball was electrified and insulated. Two hollow hemispheres of copper, of a larger size, and furnished with glass handles, were then placed together outside it (Fig. 27). So long as they did not come into contact the charge remained on the inner sphere; but if the outer shell touched the inner sphere for but an instant, the whole of the charge passed

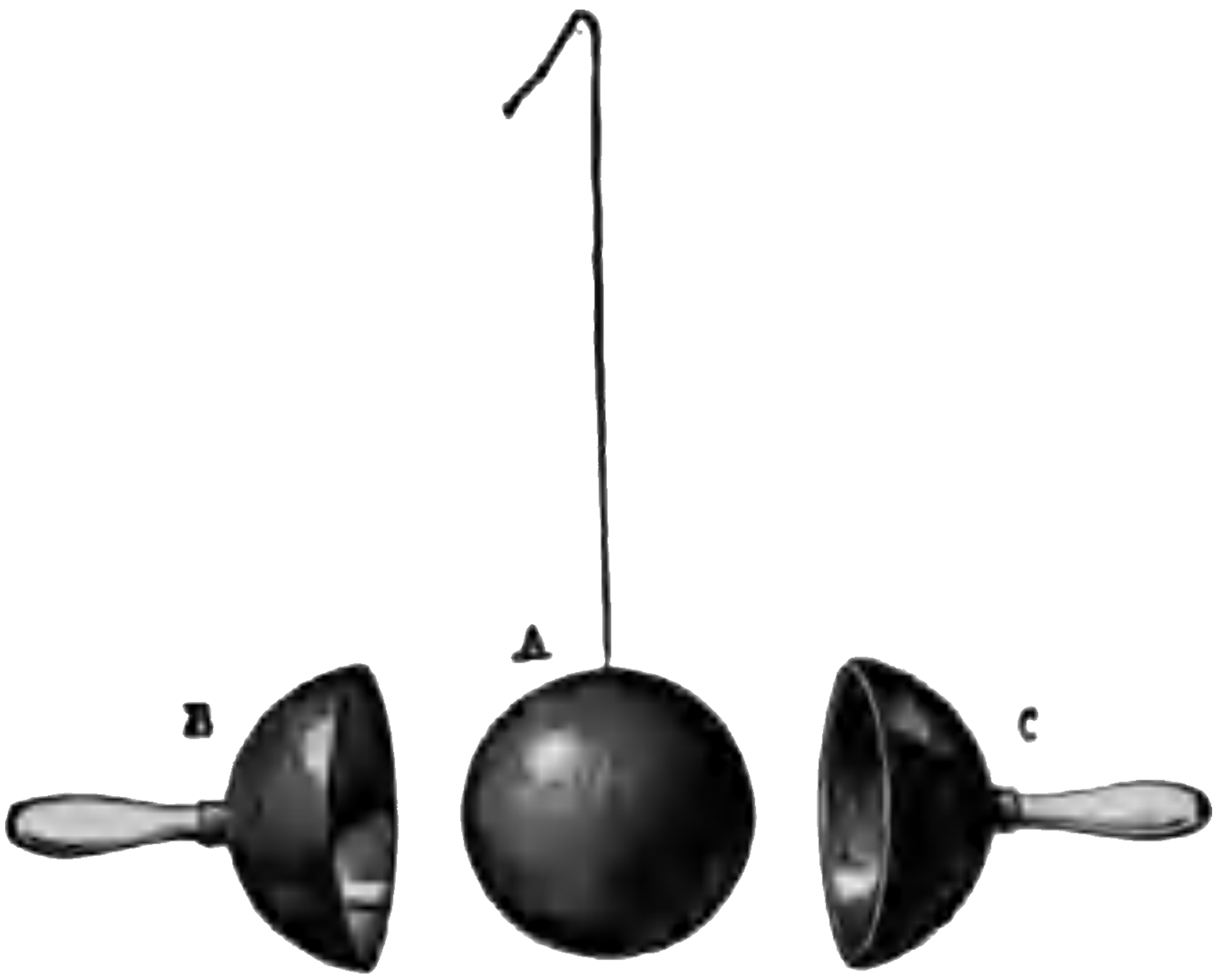


Fig. 27.

to the exterior; and when the hemispheres were separated and removed the inner globe was found to be completely discharged.

34. Further Explanation.— Doubtless the explanation of this behaviour of electricity is to be found in the property previously noticed as possessed by either kind of electrification, namely, that of repelling itself; hence it retreats as far as can be from the centre and remains upon the surface. An important proposition concerning the absence of electric force within a closed conductor is proved in Lesson XXI.; meanwhile it must be noted that the proofs, so far, are directed to demonstrate the absence

of a free charge of electricity in the interior of hollow conductors. Amongst other experiments, Terquem showed that a pair of gold leaves hung inside a wire cage could not be made to diverge when the cage was electrified. Faraday constructed a conical bag of linen-gauze, supported as in Fig. 28, upon an insulating stand, and to which silk strings were attached, by which it could be turned inside out. It was charged, and the charge was shown by the proof-plane and electroscope to be on the outside of the bag. On turning it inside out the elec-

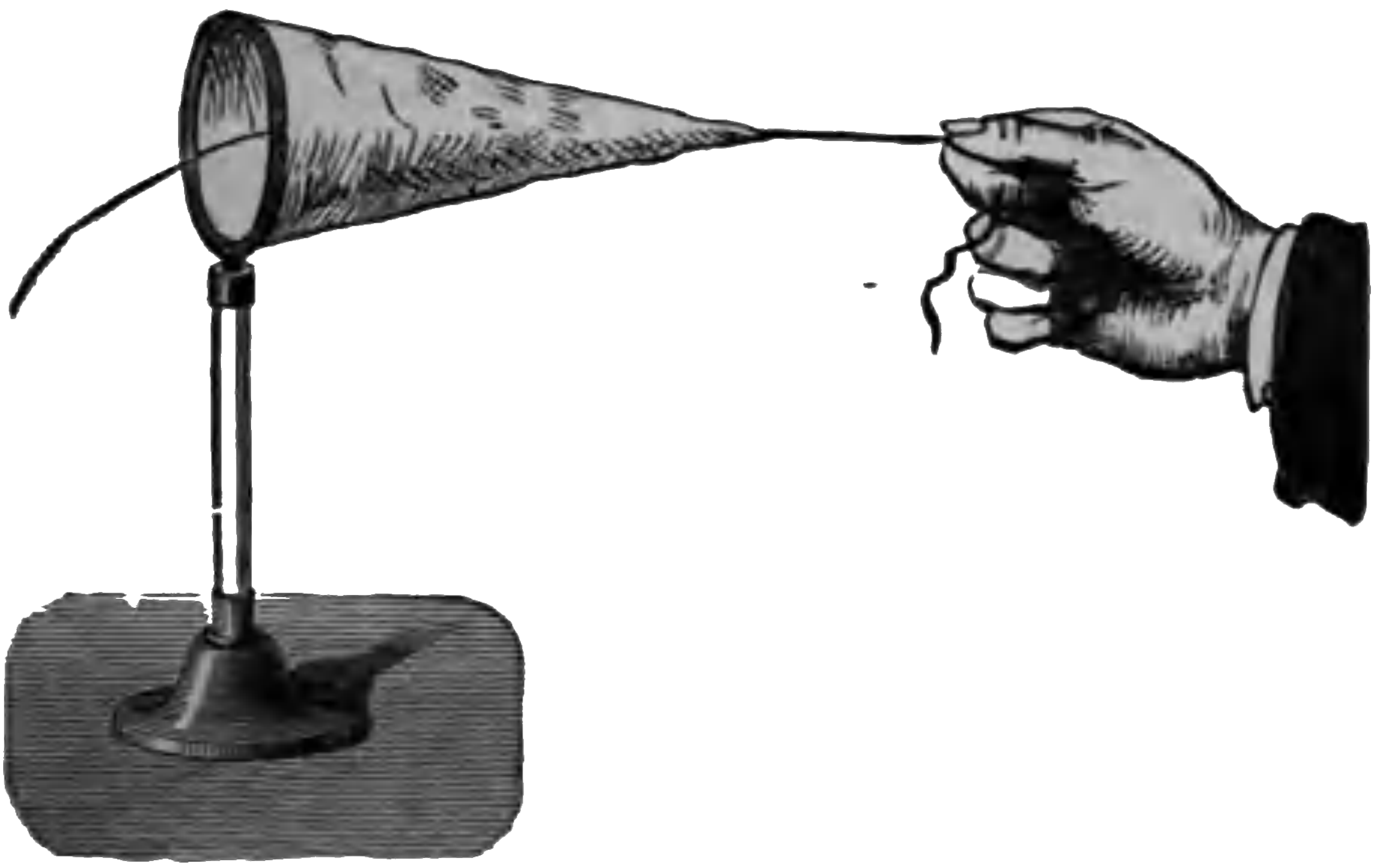


Fig. 28.

tricity was once more found *outside*. Faraday's most striking experiment was made with a hollow cube, measuring 12 feet each way, built of wood, covered with tinfoil, insulated, and charged with a powerful machine, so that large sparks and brushes were darting off from every part of its outer surface. Into this cube Faraday took his most delicate electroscopes; but once within he failed to detect the least effect upon them.

35. Applications. — Advantage is taken of this in the construction of delicate electrometers and other

instruments, which can be effectually screened from the influence of electrified bodies by enclosing them in a cover of thin metal, closed all round, except where apertures must be made for purposes of observation. Metal gauze answers excellently, and is nearly transparent. It was proposed by the late Professor Clerk Maxwell to protect buildings from lightning by covering them on the exterior with a network of wires.

36. Apparent Exceptions.—There are two apparent exceptions to the law that electrification resides only on the outside of conductors. (1) If there are electrified insulated bodies actually placed inside the hollow conductor, the presence of these electrified bodies acts inductively and attracts the opposite kind of charge to the inner side of the hollow conductor. (2) When electricity flows in a current, it flows through the substance of the conductor. The law is limited therefore to electricity at rest,—that is, to *statical* charges.

37. Faraday's "Ice-pail" Experiment.—One experiment of Faraday deserves notice, as showing the part played by induction in these phenomena. He gradually lowered a charged metallic ball into a hollow conductor connected by a wire to a gold-leaf electroscope (Fig. 29), and watched the effect. A pewter ice-pail being convenient for his purpose, this experiment is continually referred to by this name, though any other hollow conductor—a tin canister or a silver mug, placed on a glass support—would of course answer equally well. The following effects are observed:—Suppose the ball to have a + charge: as it is lowered into the hollow conductor the gold leaves begin to diverge, for the presence of the charge acts inductively, and attracts a − charge into the interior and repels a + charge to the exterior. The gold leaves diverge more and more until the ball is right within the hollow conductor, after which no greater divergence is obtained. On letting the ball touch the inside the gold leaves still remain diverging as

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shown to exist. The term **Electric Density** is used to signify the amount of electricity at any point of a surface; *the electric density at a point is the number of units of electricity per unit of area* (*i.e.* per square inch, or per square centimetre), the distribution being supposed uniform over this small surface.

(*a*) **Sphere.**—The distribution of a charge over an insulated sphere of conducting material is uniform, provided the sphere is also isolated, that is to say, is remote from the presence of all other conductors and all other electrified bodies. The density is uniform all over it. This is symbolized by the dotted line round the sphere

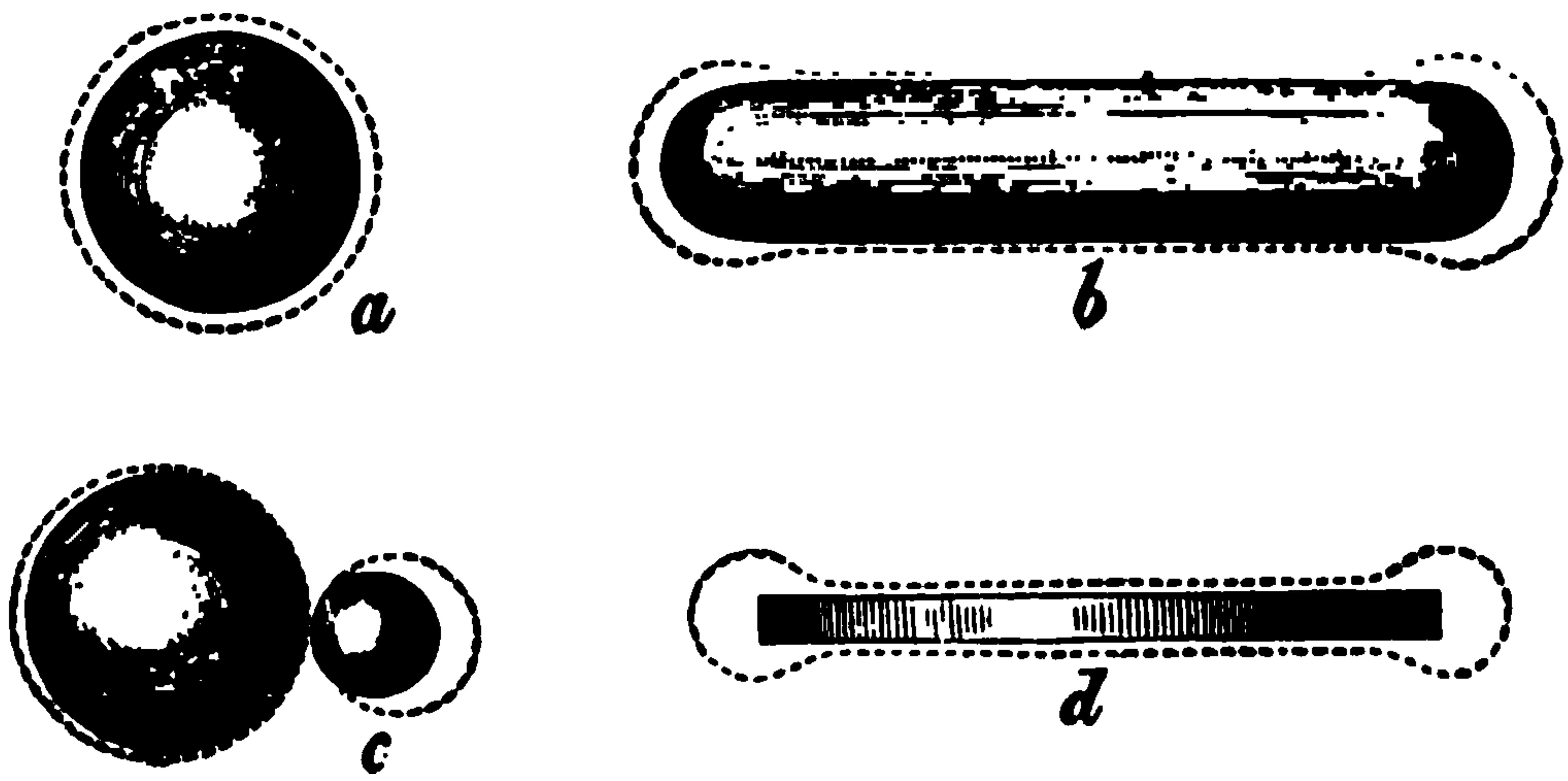


Fig. 30.

in Fig. 30 *a*, which is at an equal distance from the sphere all round, suggesting an equal thickness of charge at every point of the surface. It must be remembered that the charge is not really of any perceptible thickness at all; it resides on or at the surface, but cannot be said to form a stratum upon it.

(*b*) **Cylinder with rounded Ends.**—Upon an elongated conductor, such as is frequently employed in electrical apparatus, the density is greatest at the ends where the curvature of the surface is the greatest.

(*c*) **Two Spheres in contact.**—If two spheres in contact with each other are insulated and charged, it is found that the density is greatest at the parts farthest from the

point of contact, and least in the crevice between them. If the spheres are of unequal sizes the density is greater on the smaller sphere, which has the surface more curved. On an egg-shaped or pear-shaped conductor the density is greatest at the small end. On a cone the density is greatest at the apex; and if the cone terminate in a sharp point the density there is very much greater than at any other point. At a point, indeed, the density of the collected electricity may be so great as to electrify the neighbouring particles of air, which then are repelled (see Art. 47), thus producing a continual loss of charge. For this reason points and sharp edges are always avoided on electrical apparatus, except where it is specially desired to set up a discharge.

(*d*) **Flat Disk.**—The density of a charge upon a flat disk is greater, as we should expect, at the edges than on the flat surfaces; but over the flat surfaces the distribution is fairly uniform.

These various facts are ascertained by applying a small proof-plane successively at various points of the electrified bodies and examining the amount taken up by the proof-plane by means of an electroscope or electrometer. Coulomb, who investigated mathematically as well as experimentally many of the important cases of distribution, employed the torsion balance to verify his calculations. He investigated thus the case of the ellipsoid of revolution, and found the densities of the charges at the extremities of the axis to be proportional to the lengths of those axes. He also showed that the density of the charge at any other point of the surface of the ellipsoid was proportional to the length of the perpendicular drawn from the centre to the tangent at that point. Riess also investigated several interesting cases of distribution. He found the density at the middle of the edges of a cube to be nearly two and a half times as great as the density at the middle of a face; while the density at a corner of the cube was more than four times as great.

39. Redistribution of Charge. — If any portion of the charge of an insulated conductor be removed, the remainder of the charge will immediately redistribute itself over the surface in the same manner as the original charge, provided it be also *isolated*, *i.e.* that no other conductors or charged bodies be near to perturb the distribution by complicated effects of influence.

If a conductor be charged with any quantity of electricity, and another conductor of the same size and shape (but uncharged) be brought into contact with it for an instant and then separated, it will be found that the charge has divided itself equally between them. In the same way a charge may be divided equally into three or more parts by being distributed simultaneously over three or more equal and similar conductors brought into contact and symmetrically placed.

If two equal metal balls, suspended by silk strings, charged with unequal quantities of electricity, are brought for an instant into contact and then separated, it will be found that the charge has redistributed itself fairly, half the sum of the two charges being now the charge of each. This may even be extended to the case of charges of opposite signs. Thus, suppose two similar conductors to be electrified, one with a positive charge of 5 units and the other with 3 units of negative charge, when these are made to touch and separated, each will have a positive charge of 1 unit; for the algebraic sum of $+5$ and -3 is $+2$, which, shared between the two equal conductors, leaves $+1$ for each.

40. Capacity of Conductors. — If the conductors be unequal in size, or unlike in form, the shares taken by each in this redistribution will not be equal, but will be proportional to the electric *capacities* of the conductors. The definition of capacity in its relation to electric quantities is given in Lesson XXI., Art. 271. We may, however, make the remark, that two insulated conductors of the same form, but of different sizes, differ in their

electrical *capacity;* for the larger one must have a larger amount of electricity imparted to it in order to electrify its surface to the same degree. The term *potential* is employed in this connexion, in the following way:—A given quantity of electricity will electrify an isolated body up to a certain "potential" (or power of doing electric work) depending on its capacity. A large *quantity* of electricity imparted to a conductor of small *capacity* will electrify it up to a very high *potential;* just as a large quantity of water poured into a vessel of narrow capacity will raise the surface of the water to a high level in the vessel. The exact definition of Potential, in terms of energy spent against the electrical forces, is given in the lesson on Electrostatics (Art. 263).

It will be found convenient to refer to a positively electrified body as one electrified to a *positive or high potential;* while a negatively electrified body may be looked upon as one electrified to a *low or negative potential.* And just as we take the level of the sea as a zero level, and measure the heights of mountains above it, and the depths of mines below it, using the sea level as a convenient point of reference for differences of level, so we take the potential of the earth's surface (for the surface of the earth is always electrified to a certain degree) as *zero potential,* and use it as a convenient point of reference from which to measure differences of electric potential.

Lesson V.—*Electric Machines*

41. For the purpose of procuring larger supplies of electricity than can be obtained by the rubbing of a rod of glass or shellac, **electric machines** have been devised. All electric machines consist of two parts, one for producing, the other for collecting, the electric charges. Experience has shown that the quantities of + and − elec-

trification developed by friction upon the two surfaces rubbed against one another depend on the amount of friction, upon the extent of the surfaces rubbed, and also upon the nature of the substances used. If the two substances employed are near together on the list of electrics given in Art. 6, the electrical effect of rubbing them together will not be so great as if two substances widely separated in the series are chosen. To obtain the highest effect, the most positive and the most negative of the substances convenient for the construction of a machine should be taken, and the greatest available surface of them should be subjected to friction, the moving parts having a sufficient pressure against one another compatible with the required velocity.

The earliest form of electric machine was devised by Otto von Guericke of Magdeburg, and consisted of a globe of sulphur fixed upon a spindle, and pressed with the dry surface of the hands while being made to rotate; with this he discovered the existence of electric sparks and the repulsion of similarly electrified bodies. Sir Isaac Newton replaced Von Guericke's globe of sulphur by a globe of glass. A little later the form of the machine was improved by various German electricians; Von Bose added a collector or "prime conductor," in the shape of an iron tube, supported by a person standing on cakes of resin to insulate him, or suspended by silken strings; Winckler of Leipzig substituted a leathern cushion for the hand as a rubber; and Gordon of Erfurt rendered the machine more easy of construction by using a glass cylinder instead of a glass globe. The electricity was led from the excited cylinder or globe to the prime conductor by a metallic chain which hung over against the globe. A pointed collector was not employed until after Franklin's famous researches on the action of points. About 1760 De la Fond, Planta, Ramsden, and Cuthbertson, constructed machines having glass plates instead of cylinders. All frictional machines are, however, now

obsolete, having in recent years been quite superseded by the modern *Influence Machines.*

42. The Cylinder Electric Machine.—The Cylinder Electric Machine consists of a glass cylinder mounted on a horizontal axis capable of being turned by a handle. Against it is pressed from behind a cushion of leather stuffed with horsehair, the surface of which is covered with a powdered amalgam of zinc or tin. A flap of silk attached to the cushion passes over the cylinder, covering its upper half. In front of the cylinder stands the "prime conductor," which is made of metal, and usually

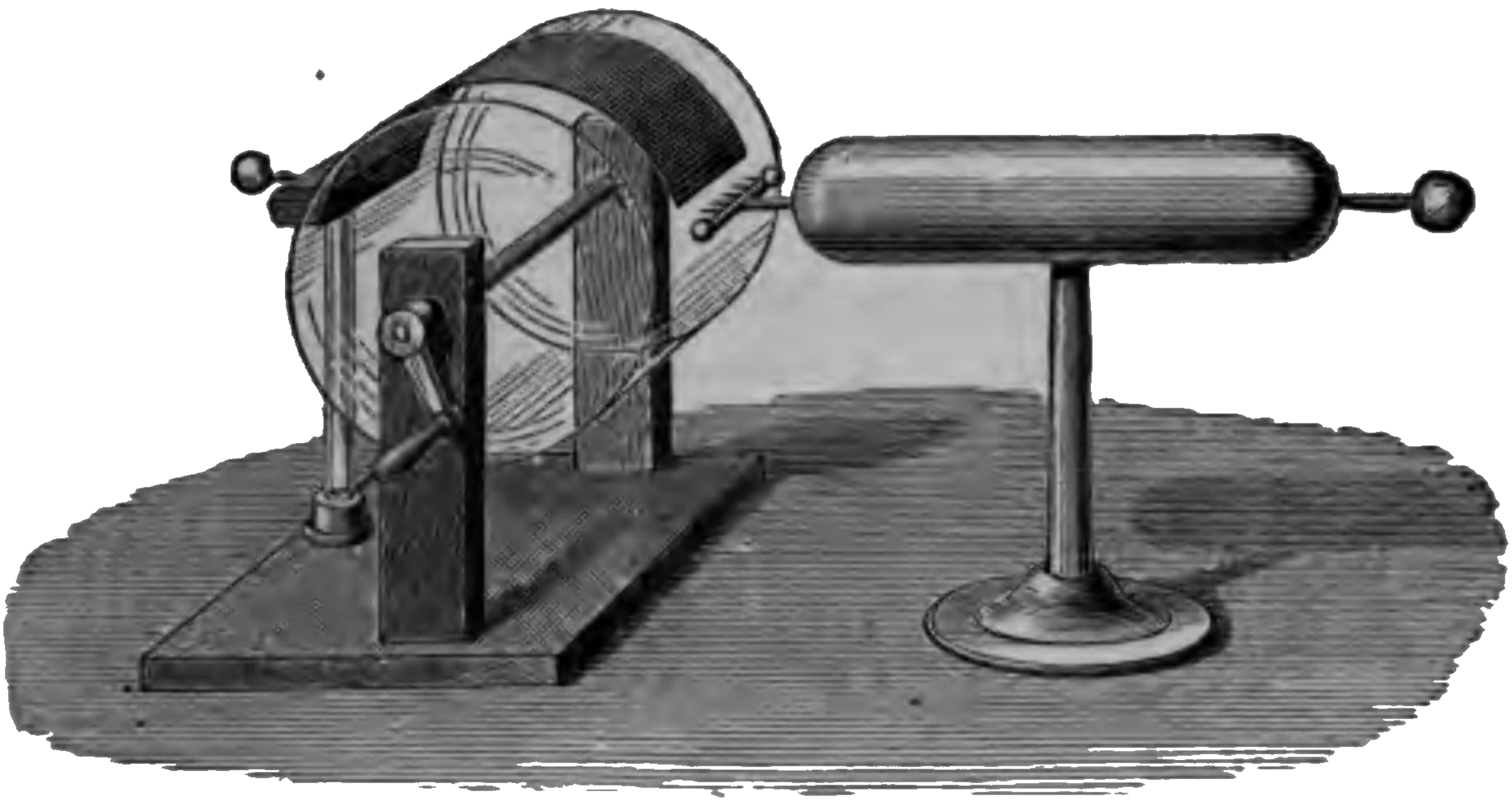


Fig. 31.

of the form of an elongated cylinder with hemispherical ends, mounted upon a glass stand. At the end of the prime conductor nearest the cylinder is fixed a rod bearing a row of fine metallic spikes, resembling in form a rake; the other end usually carries a rod terminated in a brass ball or knob. The general aspect of the machine is shown in Fig. 31. When the handle is turned the friction between the glass and the amalgam-coated surface of the rubber produces a copious electrical action, electricity appearing as a + charge on the glass, leaving the rubber with a – charge. The prime conductor col-

lects this charge by the following process:—The + charge being carried round on the glass acts inductively on the long insulated conductor, repelling a + charge to the far end; leaving the nearer end – ly charged. The effect of the row of points is to emit a – ly electrified wind (see Art. 47) towards the attracting + charge upon the glass, which is neutralized thereby; the glass thus arriving at the rubber in a neutral condition ready to be again excited. This action of the points is sometimes described, though less correctly, by saying that the points collect the + charge from the glass. If it is desired to collect also the – charge of the rubber, the cushion must be supported on an insulating stem and provided at the back with a metallic knob. It is, however, more usual to use only the + charge, and to connect the rubber by a chain to "earth," so allowing the – charge to be neutralized.

43. The Plate Electric Machine.—The Plate Machine, as its name implies, is constructed with a circular plate of glass or of ebonite, and is usually provided with two pairs of rubbers formed of double cushions, pressing the plate between them, placed at its highest and lowest point, and provided with silk flaps, each extending over a quadrant of the circle. The prime conductor is either double or curved round to meet the plate at the two ends of its horizontal diameter, and is furnished with two sets of spikes, for the same purpose

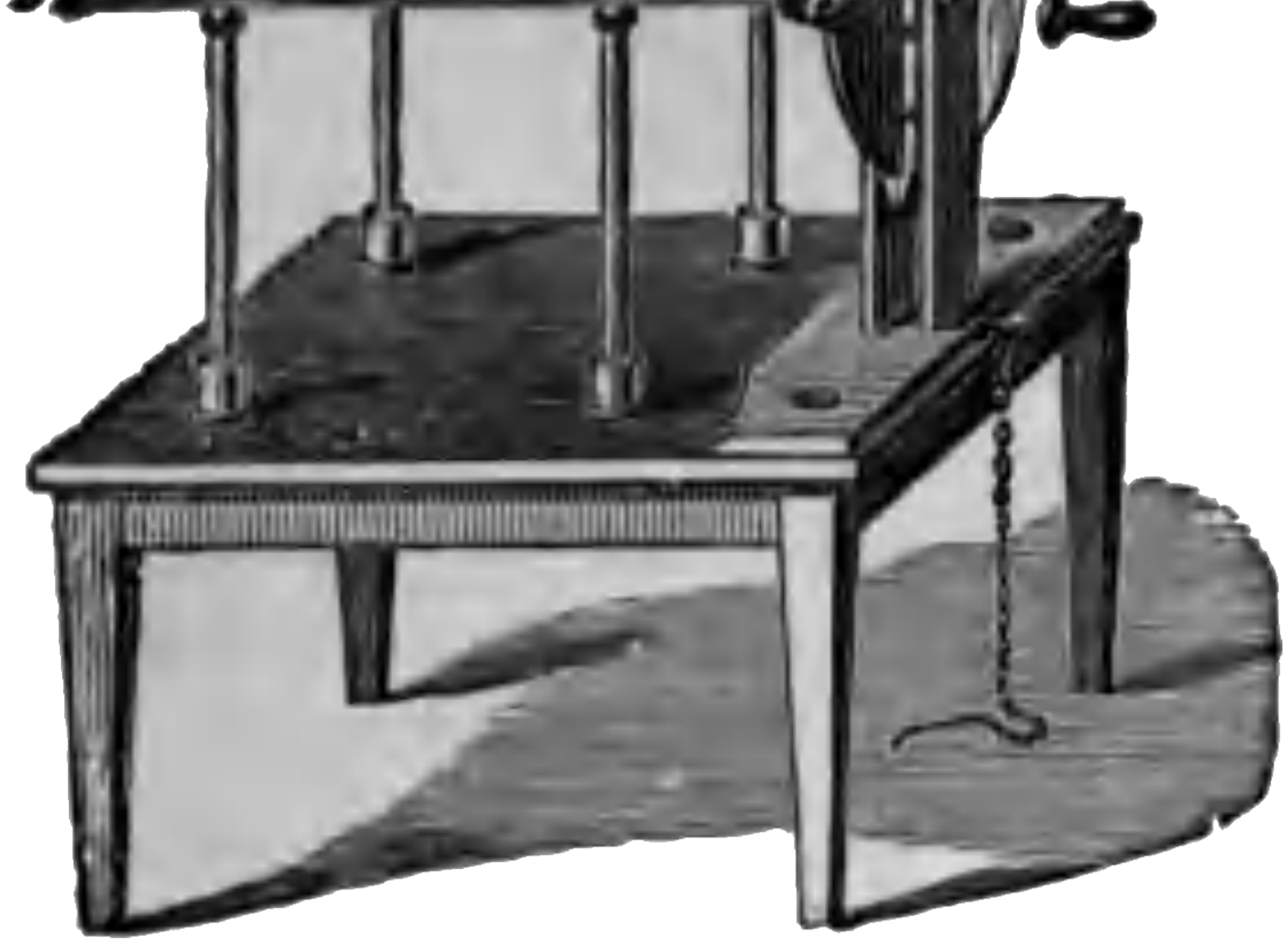


Fig. 32.

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except in the driest climates, it is necessary to warm the glass surfaces and rubbers to dissipate the film of moisture which collects. Glass stems for insulation may be varnished with a thin coat of shellac varnish, or with paraffin (solid). A few drops of anhydrous paraffin (obtained by dropping a lump of sodium into a bottle of paraffin oil), applied with a bit of flannel to the previously warmed surfaces, hinders the deposit of moisture. A frictional machine which has not been used for some months will require a fresh coat of amalgam on its rubbers. These should be cleaned and warmed, a thin uniform layer of tallow or other stiff grease is spread upon them, and the amalgam, previously reduced to a fine powder, is sifted over the surface. In spite of all precautions friction machines are uncertain in their behaviour in damp weather. This is the main reason why they have been superseded by influence machines, which do not need to be warmed.

All points should be avoided in apparatus for frictional electricity except where they are desired, like the "collecting" spikes on the prime conductor, to let off a charge of electricity. All the rods, etc., in frictional apparatus are therefore made with rounded knobs.

46. Experiments with the Electric Machine.—With the electric machine many pleasing and instructive experiments are possible. The phenomena of *attraction and repulsion* can be shown upon a large scale. Fig. 33 represents a device known as the electric chimes,* in which two small brass balls hung by silk strings are set in motion and strike against the bells between which they are hung. The two outer bells are hung by metallic wires or chains to the knob of the machine. The third bell is hung by a silk thread, but communicates with the ground by a brass chain. The balls are first attracted to

* Invented in 1752 by Franklin, for the purpose of warning him of the presence of atmospheric electricity, drawn from the air above his house by a pointed iron rod.

the electrified outer bells, then repelled, and, having discharged themselves against the uninsulated central bell, are again attracted, and so vibrate to and fro.

By another arrangement small figures or dolls cut out of pith can be made to dance up and down between a metal plate hung horizontally from the knob of the machine, and another flat plate an inch or two lower and communicating with "earth."

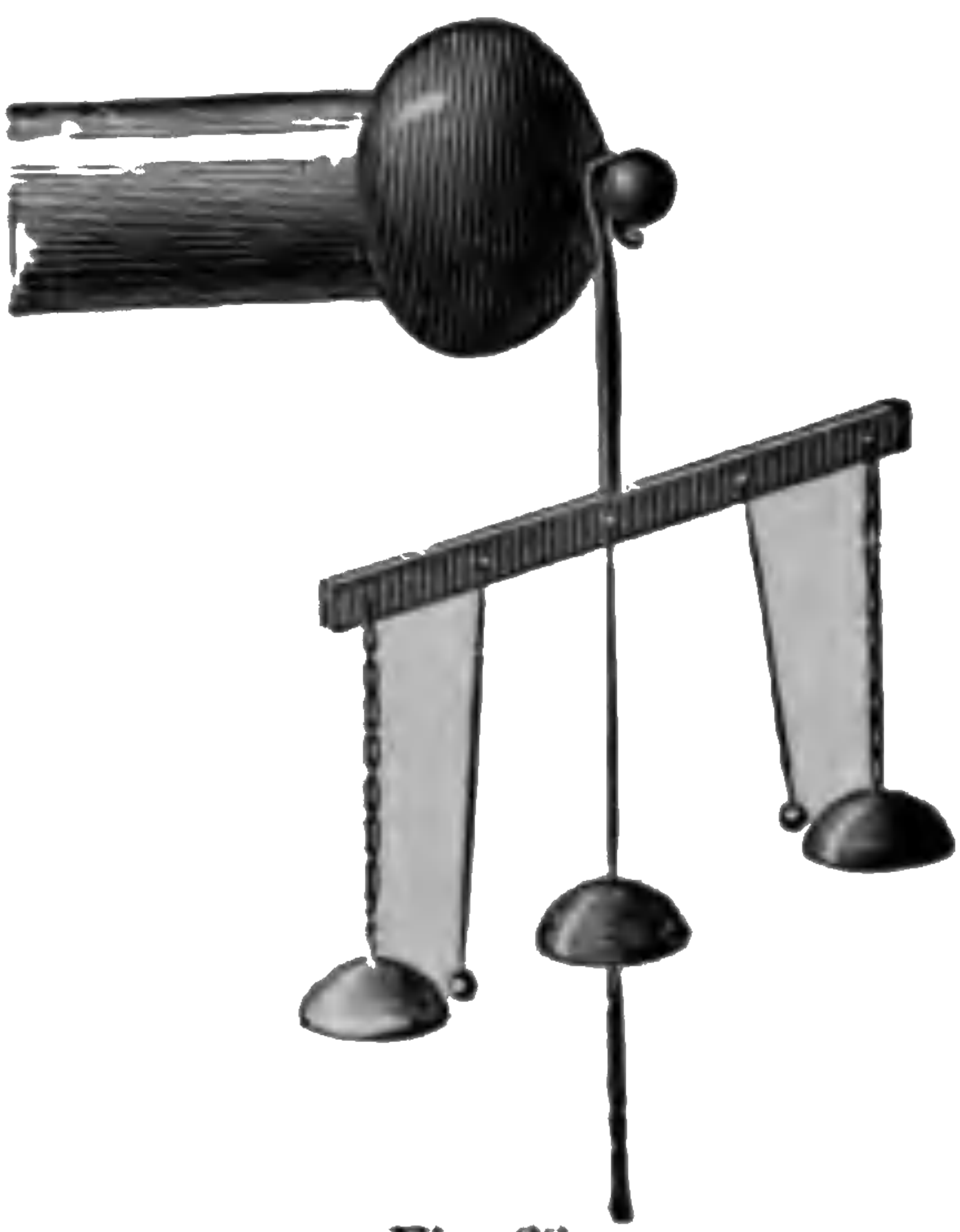


Fig. 38.

Another favourite way of exhibiting electric repulsion is by means of a doll with long hair placed on the machine; the individual hairs stand on end when the machine is worked, being repelled from the head, and from one another. A paper tassel will behave similarly if hung to the prime conductor. The most striking way of showing this phenomenon is to place a person upon a glass-legged stool, making him touch the knob of the machine; when the machine is worked, his hair, if dry, will stand on end. Sparks will pass freely between a person thus electrified and one standing upon the ground.

The sparks from the machine may be made to kindle spirits of wine or ether, placed in a metallic spoon, connected by a wire, with the nearest metallic conductor that runs into the ground. A gas jet may be lit by passing a spark to the burner from the finger of the person standing, as just described, upon an insulating stool.

47. Effect of Points; Electric Wind. — The *effect of points* in discharging electricity from the surface of a conductor may be readily proved by numerous experiments.

If the machine be in good working order, and capable of giving, say, sparks 4 inches long when the knuckle is presented to the knob, it will be found that, on fastening a fine pointed needle to the conductor, it discharges the electricity so effectually at its point that only the shortest sparks can be drawn at the knob, while a fine jet or brush of pale blue light will appear at the point. If a lighted taper be held in front of the point, the flame will be visibly blown aside (Fig. 34) by the streams of electrified air repelled from the point. These air-currents can be

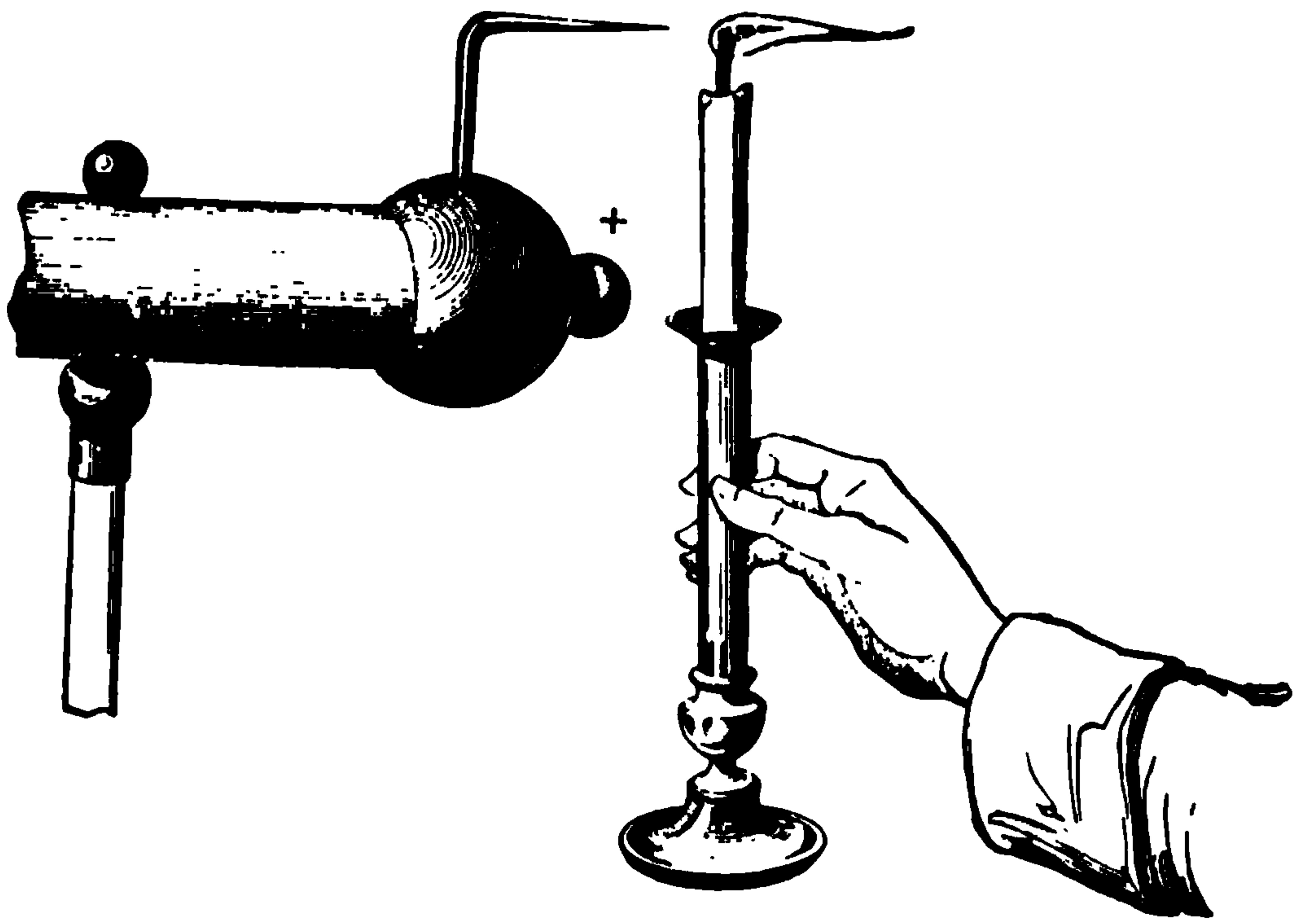


Fig. 34.

felt with the hand. They are due to a mutual repulsion between the electrified air particles near the point and the electricity collected on the point itself. That this mutual *reaction* exists is proved by the electric fly or electric reaction-mill of Hamilton (Fig. 35), which consists of a light cross of brass or straw, suspended on a pivot, and having the pointed ends bent round at right angles. When placed on the prime conductor of the machine, or joined to it by a chain, the force of repulsion between the electricity of the points and that on the air

immediately in front of them drives the mill round in the direction opposite to that in which the points are bent. It will even rotate if immersed in turpentine or petroleum. If the points of the fly are covered with small round lumps of wax it will not rotate, as the presence of the wax prevents the formation of any wind or stream of electrified particles.

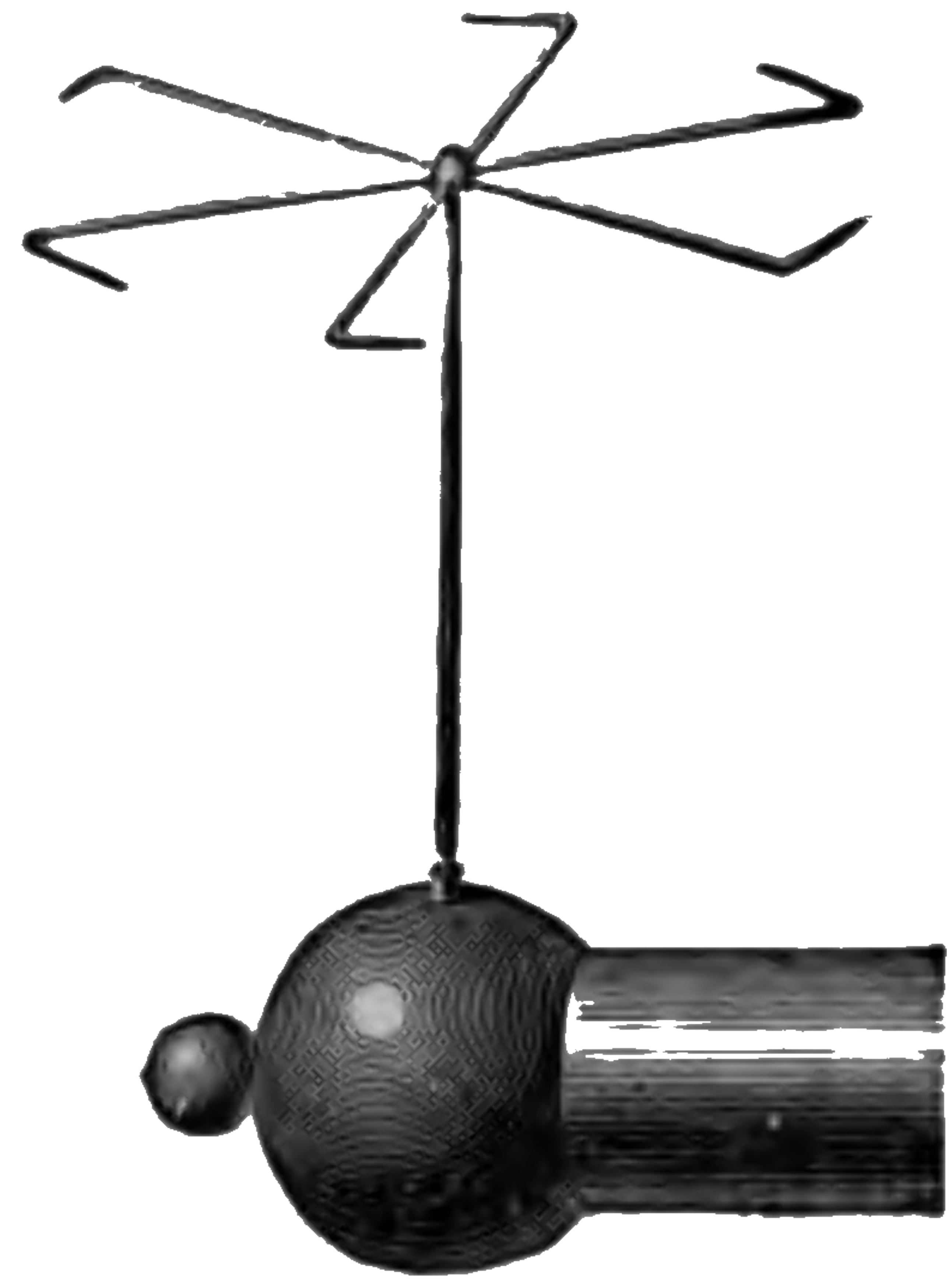


Fig. 35.

The electric wind from a point will produce a charge upon the surface of any insulating body, such as a plate of ebonite or glass, held a few inches away. The charge may be examined by dusting red lead or lycopodium powder upon the surface. If a slip of glass or mica be interposed between the point and the surface against which the wind is directed, an electric *shadow* will be formed on the surface at the part so screened.

48. Armstrong's Hydro-Electrical Machine. — The friction of a jet of steam issuing from a boiler, through a wooden nozzle, generates electricity. In reality it is the particles of condensed water in the jet which are directly concerned. Sir W. Armstrong, who investigated this source of electricity, constructed a powerful apparatus, known as the **hydro-electrical machine**, capable of producing enormous quantities of electricity, and yielding sparks 5 or 6 feet long. The collector consisted of a row of spikes, placed in the path of the steam jets issuing from wooden nozzles, and was supported, together with a brass ball which served as prime conductor, upon a glass pillar.

49. Influence Machines. — There is another class of

electrical machine, differing entirely from those we have been describing, and depending upon the principle of *influence*. They also have been termed *convection-induction machines*, because they depend upon the employment of a minute initial charge which, acting by influence, *induces* other charges, which are then *conveyed* by the moving parts of the machine to some other part, where they can be used either to increase the initial charge or to furnish a supply of electrification to a suitable collector. Of such instruments the oldest is the *Electrophorus*, explained fully in Lesson III. Bennet, Nicholson, Erasmus Darwin, and others devised pieces of apparatus for accomplishing by mechanism that which the electrophorus accomplishes by hand. Nicholson's *revolving doubler*, invented in 1788, consists of a revolving apparatus, in which an insulated carrier can be brought into the presence of an electrified body, there touched for an instant while under influence, then carried forward with its acquired charge towards another body, to which it imparts its charge, and which in turn acts inductively on it, giving it an opposite charge, which it can convey to the first body, thus increasing its initial charge at every rotation.

In the modern influence machines two principles are embodied: (1) the principle of *influence*, namely, that a conductor touched while under influence acquires a charge of the opposite kind; (2) the principle of *reciprocal accumulation*. This principle must be carefully noted. Let there be two insulated conductors A and B electrified ever so little, one positively, the other negatively. Let a third insulated conductor C, which will be called a *carrier*, be arranged to move so that it first approaches A and then B, and so forth. If touched while under the influence of the small positive charge on A it will acquire a small negative charge; suppose that it then moves on and gives this negative charge to B. Then let it be touched while under the influence of B, so acquiring a small positive charge. When it returns towards A let it give

up this positive charge to A, thereby increasing its positive charge. Then A will act more powerfully, and on repeating the former operations both B and A will become more highly charged. Each accumulates the charges derived by influence from the other. This is the fundamental action of the machines in question. The modern influence machines date from 1860, when C. F. Varley produced a form with six carriers mounted on a rotating disk of glass. This was followed in 1865 by

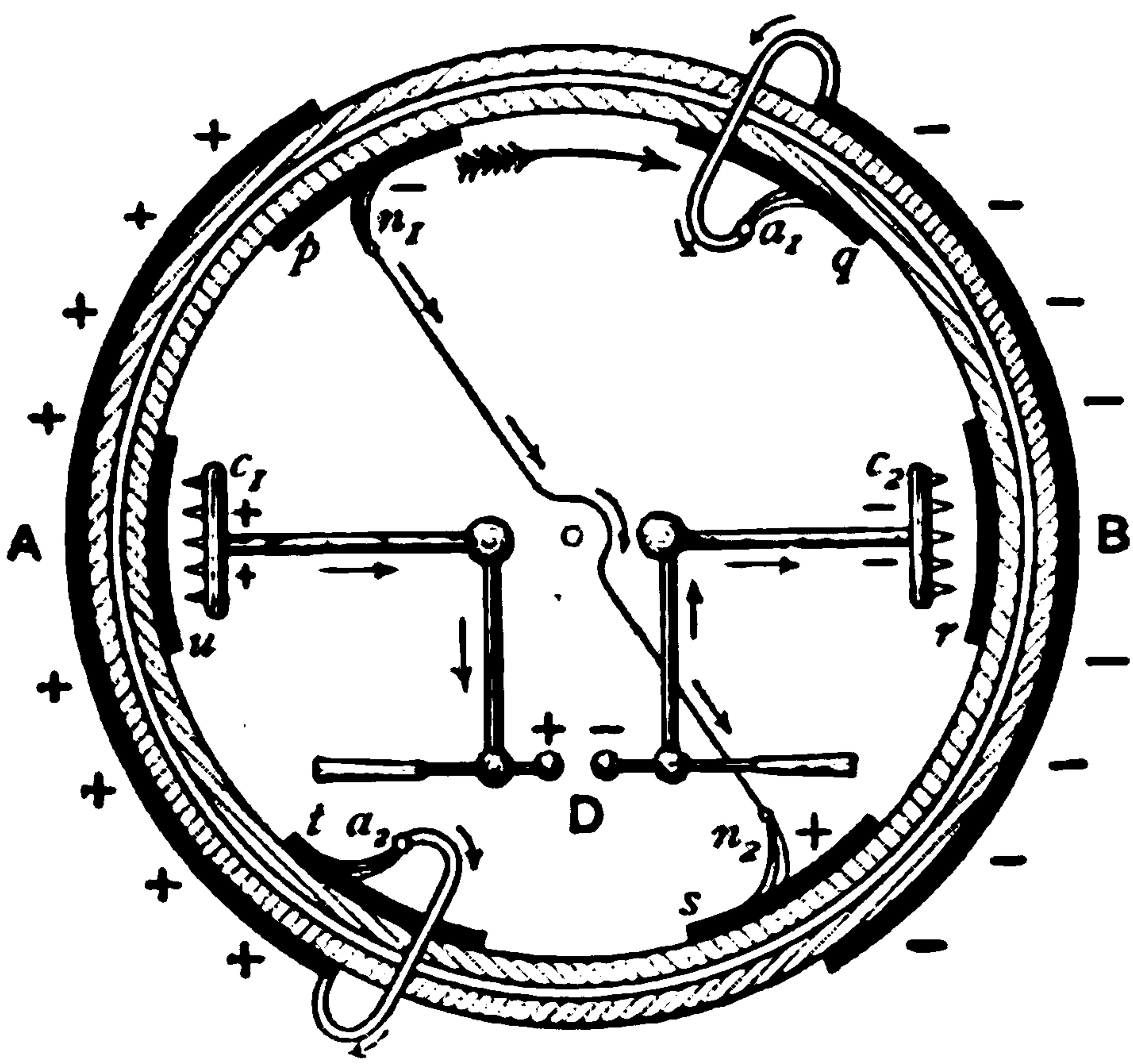


Fig. 36.

the machine of Holtz and that of Toepler, and in 1867 by those of Lord Kelvin (the "replenisher" and the "mouse-mill"). The latest forms are those of Mr. James Wimshurst.

50. **Typical Construction.** — Before describing some special forms we will deal with a generalized type of machine having two fixed *field-plates*, A and B, which are to become respectively + and −, and a set of *carriers*, attached to a rotating disk or *armature*. Fig. 36 gives in

a diagrammatic way a view of the essential parts. For convenience of drawing it is shown as if the metal field-plates A and B were affixed to the outside of an outer stationary cylinder of glass; the six carriers *p*, *q*, *r*, *s*, *t*, and *u* being attached to the inside of an inner rotating cylinder. The essential parts then are as follows:—

(i.) A pair of *field-plates* A and B.

(ii.) A set of *rotating carriers* *p*, *q*, *r*, *s*, *t*, and *u*.

(iii.) A pair of *neutralizing brushes* n_1, n_2 made of flexible metal wires, the function of which is to touch the carriers while they are under the influence of the field-plates. They are connected together by a *diagonal conductor*, which need not be insulated.

(iv.) A pair of *appropriating brushes* a_1, a_2, which reach over from the field-plates to appropriate the charges that are conveyed around by the carriers, and impart them to the field-plates.

(v.) In addition to the above, which are sufficient to constitute a complete self-exciting machine, it is usual to add a *discharging apparatus*, consisting of two *combs* c_1, c_2, to collect any unappropriated charges from the carriers after they have passed the appropriating brushes; these combs being connected to the adjustable discharging balls at D.

The operation of the machine is as follows. The neutralizing brushes are set so as to touch the moving carriers just before they pass out of the influence of the field-plates. Suppose the field-plate A to be charged ever so little positively, then the carrier *p*, touched by n_1 just as it passes, will acquire a slight negative charge, which it will convey forward to the appropriating brush a_1, and will thus make B slightly negative. Each of the carriers as it passes to the right over the top will do the same thing. Similarly each of the carriers as it passes from

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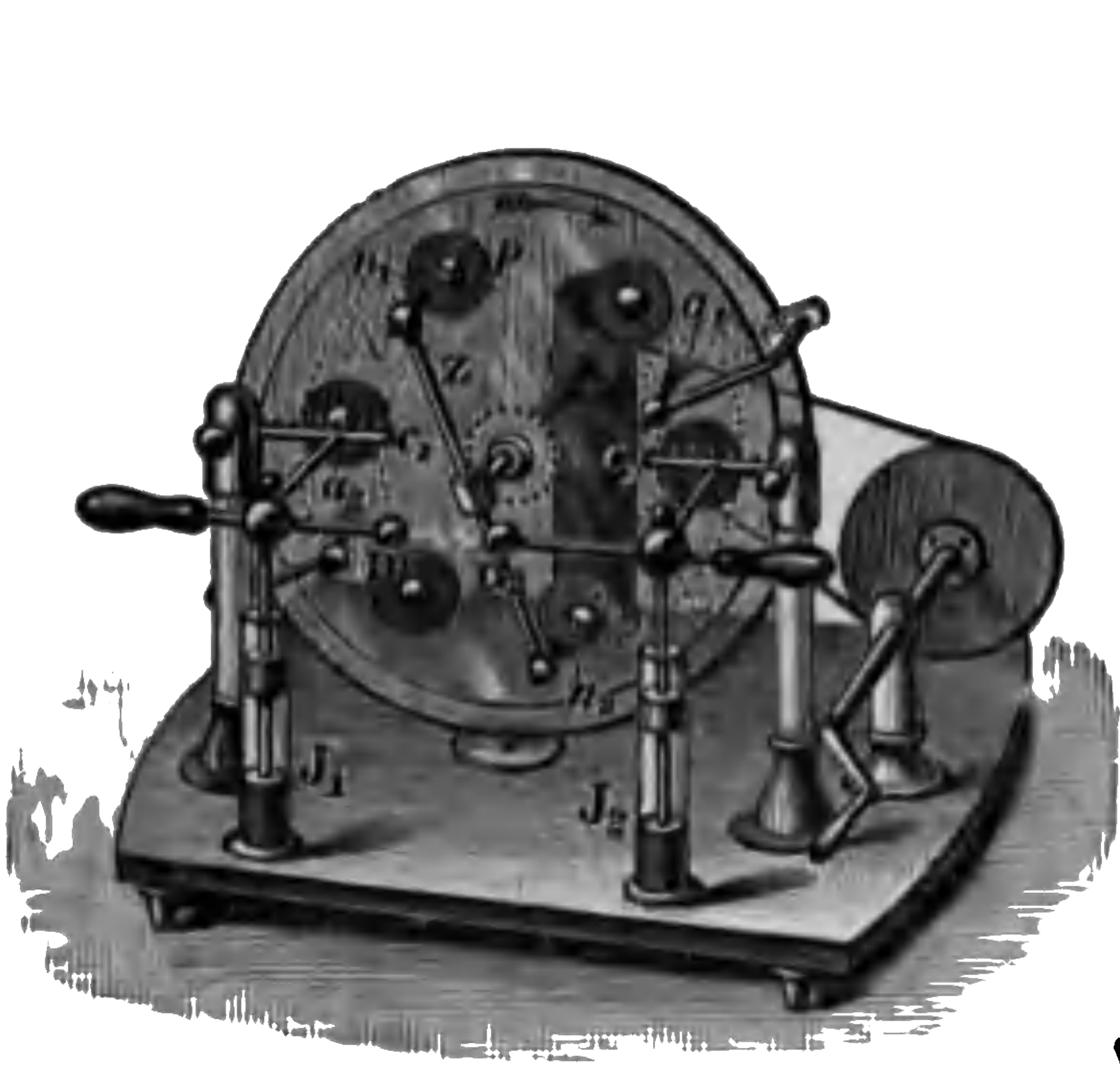
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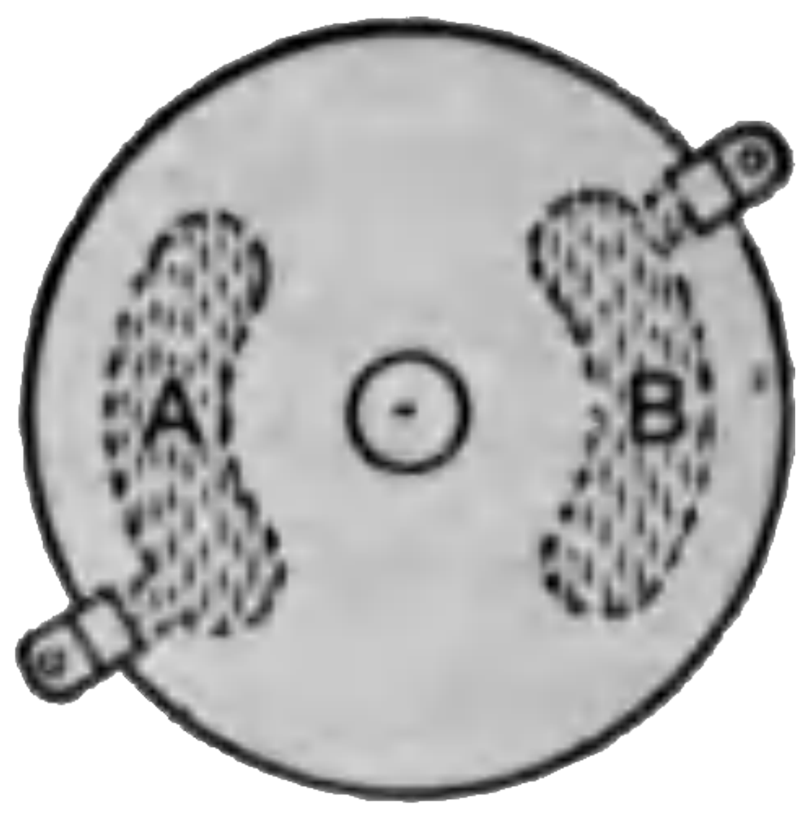
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metallic button is attached to the middle of each. The neutralizing brushes n_1, n_2 are small whisps of fine springy brass wire, and are mounted on the ends of a diagonal conductor Z. The appropriating brushes a_1, a_2 are also of thin brass wire, and are fastened to clamps projecting from the edge of the fixed disk, so that they communicate metallically with the two field-plates. The collecting combs, which have brass spikes so short as not to touch the carriers, are mounted on insulating pillars and are connected to the adjustable discharging knobs





BACK FIXED DISK WITH FIELD PLATES ON BACK.



FRONT ROTATING DISK WITH CARRIERS ON FRONT.

Fig. 37.

D_1, D_2. These also communicate with two small Leyden jars J_1, J_2, the function of which is to accumulate the charges before any discharge takes place. These jars are separately depicted in Fig. 38. Without them, the discharges between the knobs take place in frequent thin blue sparks. With them the sparks are less numerous, but very brilliant and noisy.

To use the Toepler (Voss) machine first see that all the four brushes are so set as to make good metallic contact with the carriers as they move past, and that the

neutralizing brushes are set so as to touch the carriers while under influence. Then see that the discharging knobs are drawn widely apart. Set the machine in rotation briskly. If it is clean it should excite itself after a couple of turns, and will emit a gentle hissing sound, due to internal discharges (visible as blue glimmers in the dark), and will offer more resistance to turning. If then the knobs are pushed nearer together sparks will pass across between them. The jars (the addition of which we owe to Holtz) should be kept free from dust. Sometimes a pair of terminal screws are added at S_1, S_2 (Fig. 38), connected respectively with the outer coatings

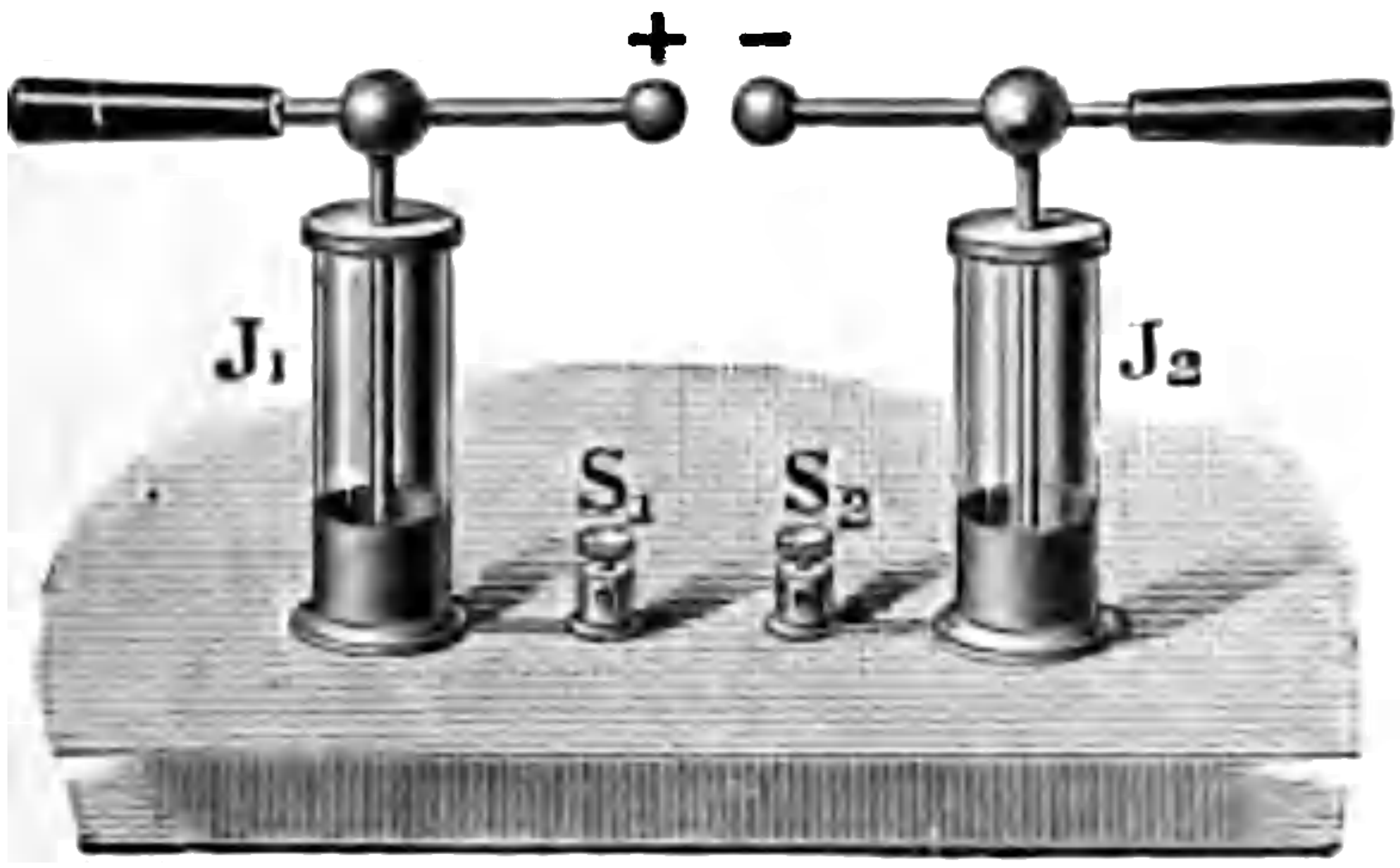


Fig. 38.

of the jars. These are convenient for attaching wires to lead away discharges for experiments at a distance. If not so used they should be joined together by a short wire, as the two jars will not work properly unless their outer coatings are connected.

52. Wimshurst's Influence Machine. — In this, the most widely used of influence machines, there are no fixed field-plates. In its simplest form it consists (Fig. 39) of two circular plates of varnished glass, which are geared to rotate in opposite directions. A number of sectors of metal foil are cemented to the front of the front plate and to the back of the back plate; these sectors serve both as carriers and as inductors. Across

the front is fixed an uninsulated diagonal conductor, carrying at its ends neutralizing brushes, which touch the front sectors as they pass. Across the back, but sloping the other way, is a second diagonal conductor, with brushes that touch the sectors on the hinder plate. Nothing more than this is needed for the machine to excite itself when set in rotation; but for convenience

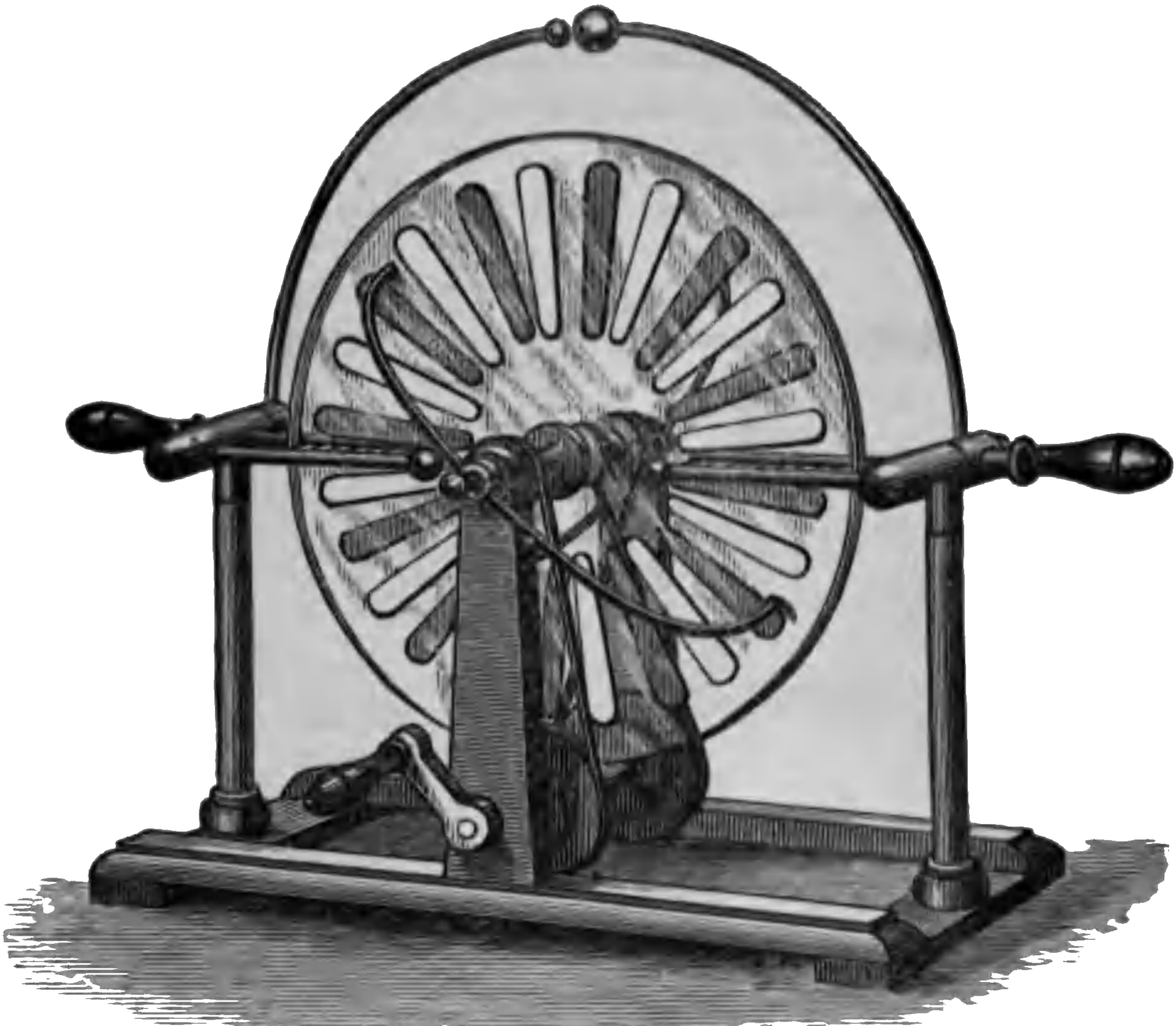


Fig. 39.

there is added a collecting and discharging apparatus. This consists of two pairs of insulated combs, each pair having its spikes turned inwards toward the revolving disks, but not touching them; one pair being on the right, the other on the left, mounted each on an insulating pillar of ebonite. These collectors are furnished with a pair of adjustable discharging knobs overhead;

and sometimes a pair of Leyden jars is added, to prevent the sparks from passing until considerable quantities of charge have been collected.

The processes that occur in this machine are best explained by aid of a diagram (Fig. 40), in which, for greater clearness, the two rotating plates are represented

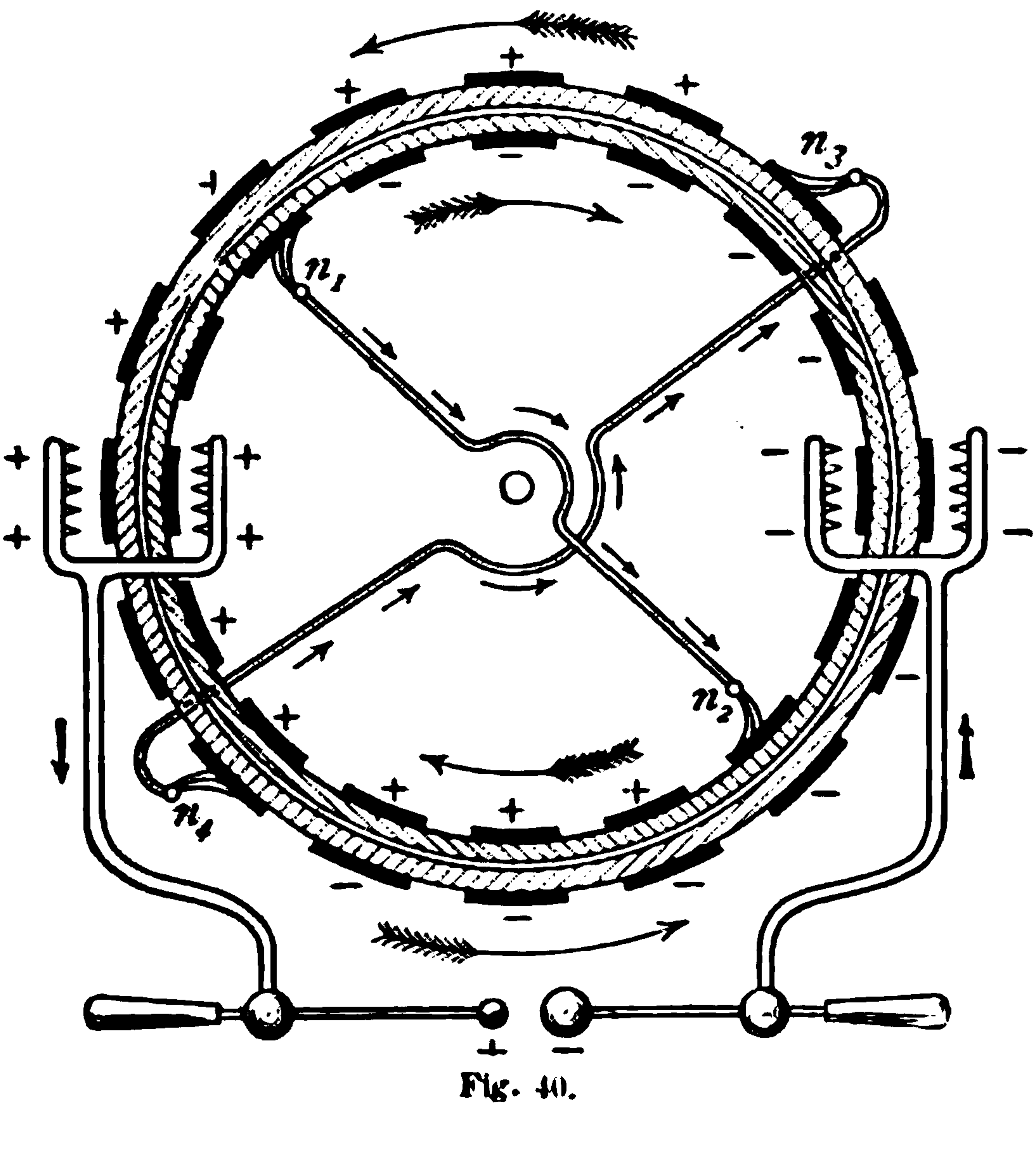


Fig. 40.

as though they were two cylinders of glass, rotating opposite ways, one inside the other. The inner cylinder will represent the front plate, the outer the back plate. In Figs. 39 and 40 the front plate rotates right-handedly, the back plate left-handedly. The neutralizing brushes n_1, n_2 touch the front sectors, while n_3, n_4 touch against the back sectors.

Now suppose any one of the back sectors represented near the top of the diagram to receive a slight positive charge. As it is moved onward toward the left it will come opposite the place where one of the front sectors is moving past the brush n_1. The result will be that the sector so touched while under influence by n_1 will acquire a slight negative charge, which it will carry onwards toward the right. When this negatively-charged front sector arrives at a point opposite n_3 it acts inductively on the back sector which is being touched by n_3; hence this back sector will in turn acquire a positive charge, which it will carry over to the left. In this way all the sectors will become more and more highly charged, the front sectors carrying over negative charges from left to right, and the back sectors carrying over positive charges from right to left. At the lower half of the diagram a similar but inverse set of operations will be taking place. For when n_1 touches a front sector under the influence of a positive back sector, a repelled charge will travel along the diagonal conductor to n_2, helping to charge positively the sector which it touches. The front sectors, as they pass from right to left (in the lower half), will carry positive charges, while the back sectors, after touching n_4, will carry negative charges from left to right. The metal sectors then act both as carriers and as inductors. It is clear that there will be a continual carrying of positive charges toward the right, and of negative charges to the left. At these points, toward which the opposite kinds of charges travel, are placed the collecting-combs communicating with the discharging knobs. The latter ought to be opened wide apart when starting the machine, and moved together after it has excited itself.

In larger Wimshurst influence machines two, three, or more pairs of oppositely-rotating plates are mounted within a glass case to keep off the dust. If the neutralizing brushes make good metallic contact these machines are all self-exciting in all weathers. Machines with only

six or eight sectors on each plate give longer sparks, but less frequently than those that have a greater number. Mr. Wimshurst has designed many influence machines, from small ones with disks 2 inches across up to that at South Kensington, which has plates 7 feet in diameter.

Prior to Wimshurst's machine Holtz had constructed one with two oppositely-rotating glass disks; but they had no metal carriers upon them. It was not self-exciting.

53. **Holtz's Influence Machine.** — The Holtz machine in its typical form had the following peculiarities. There were no metal carriers upon the rotating plate, hence another mode of charging it had to be adopted in lieu of touching conductors while under influence, as will be seen. The field-plates A and B (Fig. 41) were of varnished paper — a poor conductor — fastened upon the back of the fixed disk. In the fixed disk of glass, on which the field-plates were mounted, there were cut two windows or openings, through which there projected from the field-plates two pointed paper tongues, which took the place of appropriating brushes. The discharging knobs were inserted in the neutralizing circuit which united two metal combs with pointed spikes, situated in front of the rotating front disk, opposite the two field-plates. There was (at first) no diagonal conductor. It will be noted that while the combs, which served both as neutralizing and collecting combs, were in front of the rotating plate, the appropriating tongues were situated at the back of the same. Fig. 41 is a view of the machine from behind. The machine was not self-exciting. In operating it the following procedure

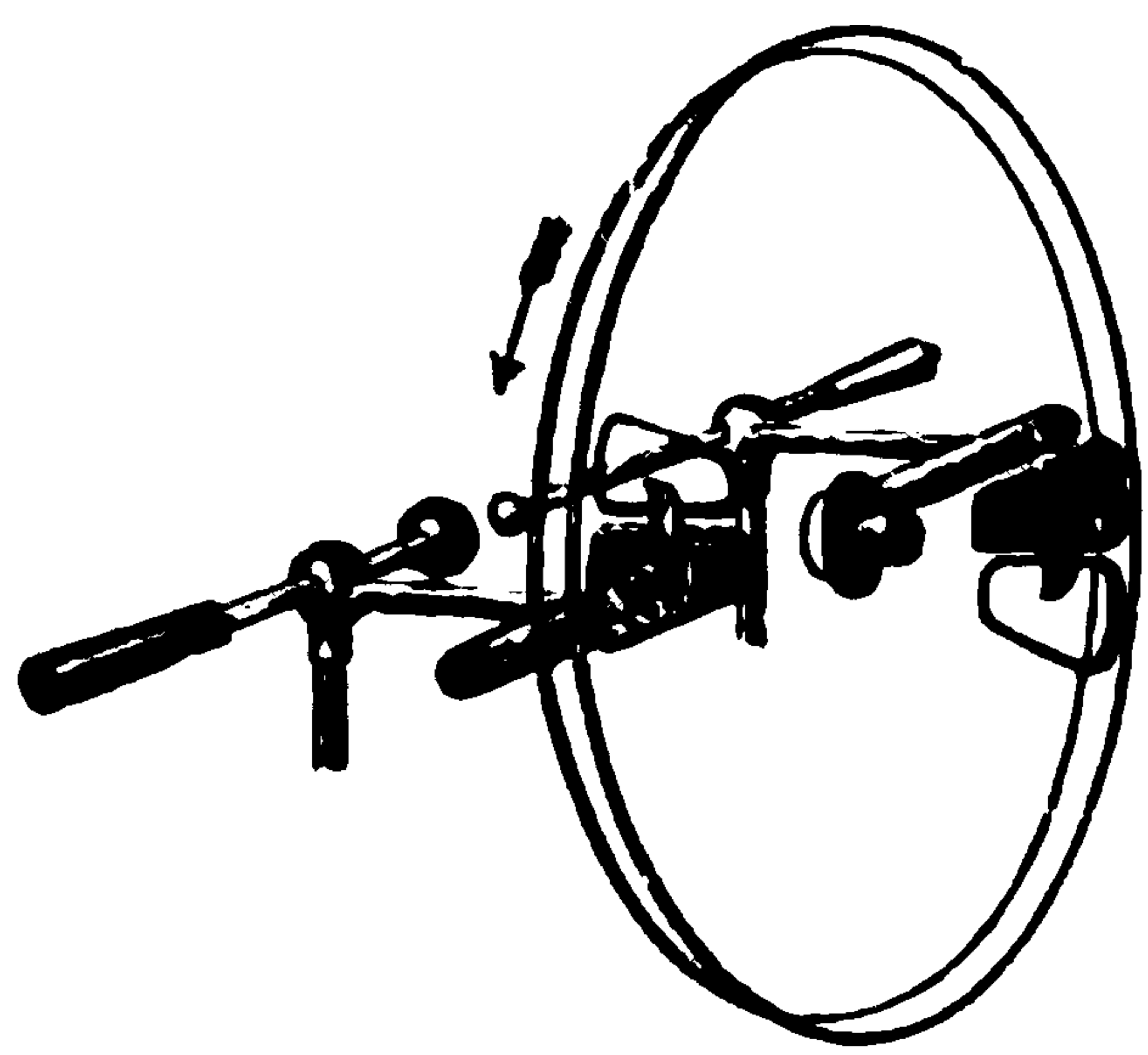


Fig. 41.

was used: first the two discharging knobs were put together, then the front disk was set into rapid rotation. While so rotating a small initial charge was communicated to one of the field-plates by holding to it a rubbed piece of ebonite or glass, or by sending into it a spark from a Leyden jar. Thereupon the machine charged itself, and began to emit pale blue sparks from the points of the combs and tongues with a hissing sound. On then drawing apart the discharging knobs, a torrent of sparks rushed across.

These arrangements being known, it is not difficult to follow the action of the machine, provided it is once understood that the whole operation depends upon the circumstance that the surface of a non-conducting body such as glass can be electrified by letting off against it an electric wind from a point placed near it (see Art. 47). Suppose that a small initial + charge is given to A. This will operate by influence upon the metal parts immediately opposite it, and cause the spikes to become electrified negatively, and to give off a negatively electrified wind, which will charge the face of the rotating plate, these charges being then carried over to the other side, where the spikes of the other comb will be emitting a positively electrified wind. The pointed tongues which project towards the back of the rotating disk also let off winds, the tendency being always for them to charge the back of the plate with a charge of opposite sign from that which is coming toward them on the front. If negative charges are being carried over the top on the front, then the tongue of B will tend to let off a positive charge against the back, thereby leaving B more negative. In the same way the tongue of A will let off a negatively electrified wind, making A more positive, so building up or accumulating two opposite kinds of charges on the two field-plates. This action will not occur unless the moving plate rotates in the direction opposite to that in which the two tongues point.

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may be connected by guttapercha-covered wires to the two discharging knobs, or to the terminals S_1, S_2 of Fig. 38. The curious property of the electric discharge from a point in collecting *dust* or fumes is readily shown by connecting by a wire a needle which is introduced into a bell-jar of glass. The latter is filled with fumes by burning inside it a bit of magnesium wire, or of brown paper. Then on turning the handle of the influence machine the fumes are at once deposited, and the air left clear.

Lesson VI.—*The Leyden Jar and other Condensers*

55. It was shown in previous lessons that the opposite charges of electricity attract one another; that electricity cannot flow through glass; and that yet electricity can *act across* glass by influence. Two suspended pith-balls, one electrified positively and the other negatively, will attract one another across the intervening air. If a plate of glass be put between them they will still attract one another, though neither they themselves nor the electric charges on them can pass through the glass. If a pith-ball electrified with a – charge be hung inside a dry glass bottle, and a rubbed glass rod be held outside, the pith-ball will rush to the side of the bottle nearest to the glass rod, being attracted by the + charge thus brought near it. If a pane of glass be taken, and a piece of tinfoil be stuck upon the middle of each face of the pane, and one piece of tinfoil be charged positively, and the other negatively, the two charges will attract one another across the glass, and will no longer be found to be free. If the pane is set up on edge, so that neither piece of tinfoil touches the table, it will be found that hardly any electricity can be got by merely touching either of the foils, for the charges are "bound," so to speak, by each other's attractions; each charge is inducing the other. In fact it will be

found that these two pieces of tinfoil may be, in this manner, charged a great deal more strongly than either of them could possibly be if it were stuck to a piece of glass alone, and then electrified. In other words, *the capacity of a conductor is greatly increased when it is placed near to a conductor electrified with the opposite kind of charge.* If its capacity is increased, a greater quantity of electricity may be put into it before it is charged to an equal degree of potential. Hence, such an arrangement for holding a large quantity of electrification may be called a **condenser** of electricity.

56. Condensers. — Next, suppose that we have two brass disks, A and B (Fig. 42), set upon insulating stems, and that a glass plate is placed between them. Let B be connected by a wire to the knob of an electrical machine, and let A be joined by a wire to "earth." The + charge upon B will act inductively across the glass plate on A, and will repel electricity into the earth, leaving the nearest face of A negatively electrified. This – charge on A will attract the + charge of B to the side nearest the glass, and a fresh supply of electricity will come from the machine. Thus this arrangement will become a condenser. If the two brass disks are pushed up close to the glass plate there will be a still stronger attraction between the + and – charges, because they are now nearer one another, and the inductive action will be greater; hence a still larger quantity can be accumulated in the plates. We see then that the capacity of a condenser is increased by bringing the plates near together. If now, while the disks are strongly charged, the wires are removed and the

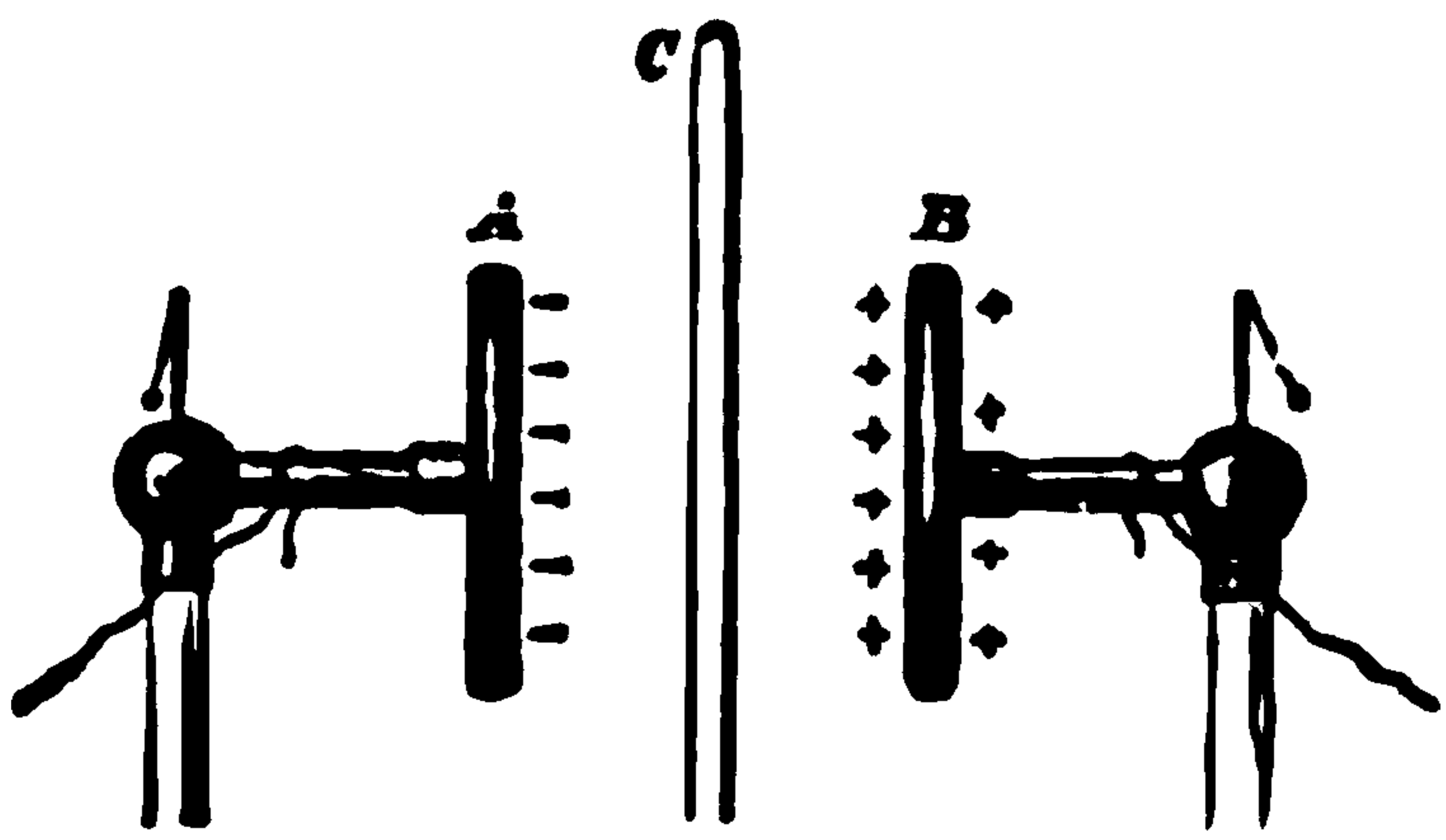


Fig. 42.

disks are drawn backwards from one another, the two charges will not hold one another bound so strongly, and there will be more *free* electrification than before over their surfaces. This would be rendered evident to the experimenter by the little pith-ball electroscopes fixed to them (see the Fig.), which would fly out as the brass disks were moved apart. We have put no further charge on the disk B, and yet, from the indications of the electroscope, we should conclude that by moving it away from disk A it has become electrified to a higher degree. The fact is, that while the conductor B was near the – charge of A the *capacity* of B was greatly increased, but on moving it away from A its capacity has diminished, and hence the same quantity of electricity now electrifies it to a higher degree than before. The presence, therefore, of an earth-connected plate near an insulated conductor increases its capacity, and permits it to accumulate a greater charge by attracting and *condensing* the electricity upon the face nearest the earth-plate, the surface-density on this face being therefore very great; hence the appropriateness of the term *condenser* as applied to the arrangement. It was formerly also called an accumulator; but the term *accumulator* is now reserved for the special kind of battery for storing the energy of electric currents (Art. 492).

The stratum of *air* between the two disks will suffice to insulate the two charges one from the other. The brass disks thus separated by a stratum of air constitute an air-condenser, or air-leyden. Such condensers were first devised by Wilcke and Aepinus. In these experiments the sheet of glass or layer of air acts as a *dielectric* (Art. 295) conveying the inductive action through its substance. All dielectrics are insulators, but equally good insulators are not necessarily equally good dielectrics. Air and glass are far better insulators than ebonite or paraffin in the sense of being much worse conductors. But influence acts more strongly across a slab of glass than across a slab of ebonite or paraffin of equal thickness,

and better still across these than across a layer of air. In other words, glass is a better dielectric than ebonite, or paraffin, or air, as it possesses a higher inductive capacity.

It will then be seen that in the act of charging a condenser, as much electricity flows out at one side as flows in at the other.

57. **Displacement.** — Whenever electric forces act on a dielectric, tending to drive electricity in at one side and out at the other, we may draw lines of force through the dielectric in the direction of the action, and we may consider tubular spaces mapped out by such lines. We may consider a tube of electric force having at one end a definite area of the positively charged surface, and at the other end an area of the negatively charged surface. These areas may be of different size or shape, but the quantities of + and − electrification over them will be equal. The quantity of electricity which has apparently been transferred along the tube was called by Maxwell "the *displacement*." In non-conductors it is proportional to the electromotive-force. In conductors electromotive forces produce currents, which may be regarded as displacements which increase continuously with time. In certain crystalline media the displacement does not take place exactly in the direction of the electric force: in this case we should speak of tubes of influence rather than tubes of force. A unit tube will be bounded at its two ends by unit charges + and −. We may consider the whole electric field between positively and negatively charged bodies as mapped out into such tubes.

58. **Capacity of a Condenser.** — It appears, therefore, that the capacity of a condenser will depend upon —

(1) The size and form of the metal plates or coatings.

(2) The thinness of the stratum of dielectric between them; and

(3) The dielectric capacity of the material.

59. **The Leyden Jar.** — The Leyden jar, called after the city where it was invented, is a convenient form of

condenser. It usually consists (Fig. 43) of a glass jar coated up to a certain height on the inside and outside with tinfoil. A brass knob fixed on the end of a stout brass wire passes downward through a lid or top of dry well-varnished wood, and communicates by a loose bit of brass chain with the inner coating of foil. To charge the jar the knob is held to the prime conductor of an electrical machine, the outer coating being either held in the hand or connected to "earth" by a wire or chain. When a + charge of electricity is imparted thus to the inner coating, it acts inductively on the outer coating, attracting a − charge into the face of the outer coating nearest the glass, and repelling a + charge to the outside of the outer coating, and thence through the hand or wire to earth. After a few moments the jar will have acquired its full charge, the outer coating being − and the inner +. If the jar is of good glass, and dry, and free from dust, it will retain its charge for many hours or days. But if a path be provided by which the two mutually attracting electricities can flow to one another, they will do so, and the jar will be instantaneously discharged. If the outer coating be grasped with one hand, and the knuckle of the other hand be presented to the knob of the jar, a bright spark will pass between the knob and the knuckle with a sharp report, and at the same moment a convulsive "shock" will be communicated to the muscles of the wrists, elbows, and shoulders. A safer means of discharging the jar is afforded by the discharging tongs or discharger (Fig. 44), which consists of a jointed brass rod provided with brass knobs and a glass handle. One knob is laid against the outer coating, the other is then



Fig. 43.

brought near the knob of the jar, and a bright snapping spark leaping from knob to knob announces that the two accumulated charges have flowed together, completing the discharge. Sometimes a jar discharges itself by a spark climbing over the top edge of the jar. Often when a jar is well charged a hissing sound is heard, due to partial discharges creeping over the edge. They can be seen in the dark as pale phosphorescent streams.

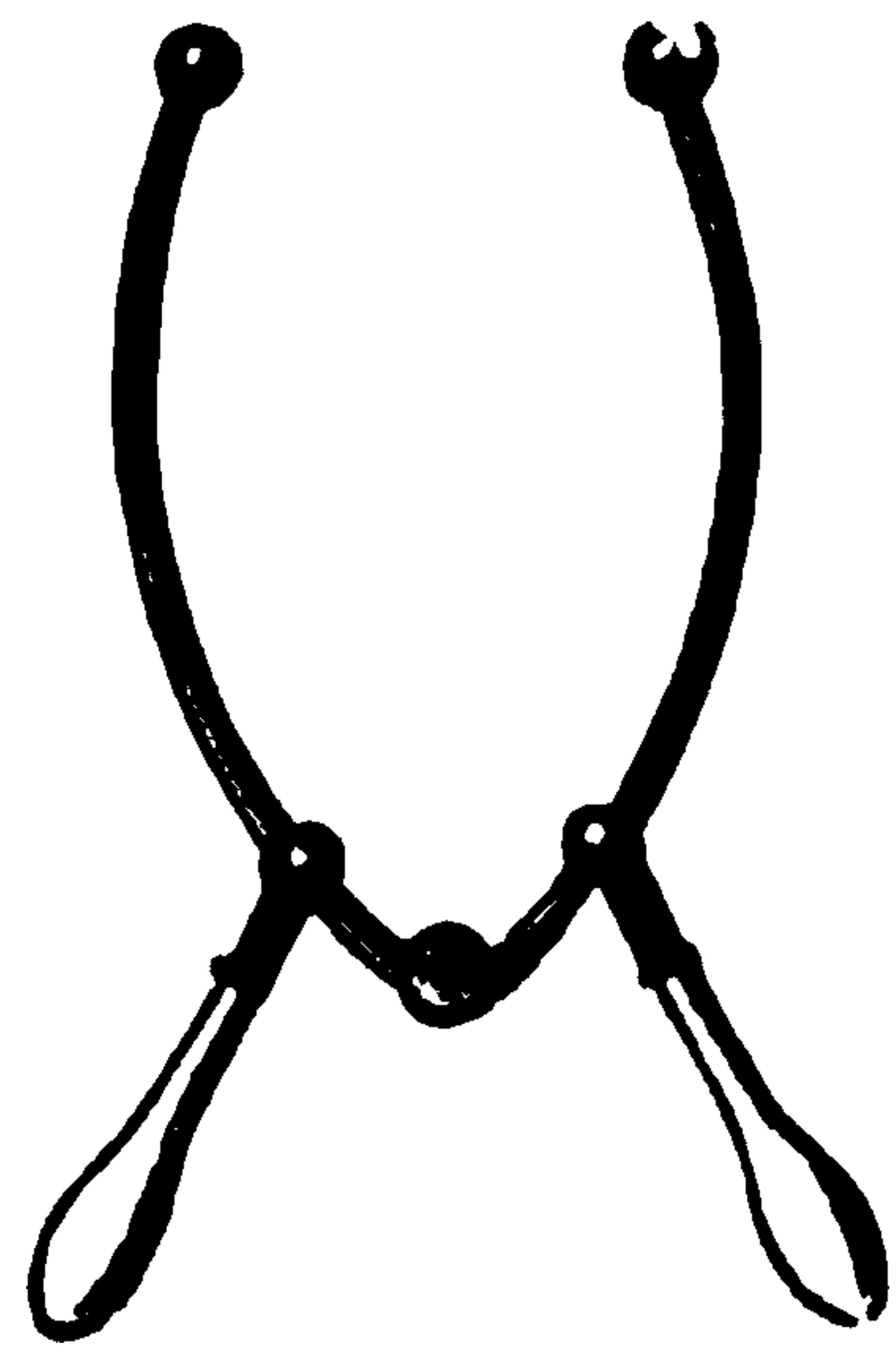


Fig. 44.

60. Discovery of the Leyden Jar.—The discovery of the Leyden jar arose from the attempt of Musschenbroek and his pupil Cuneus* to collect the supposed electric "fluid" in a bottle half filled with water, which was held in the hand and was provided with a nail to lead the "fluid" down through the cork to the water from the electric machine. Here the water served as an inner coating and the hand as an outer coating to the jar. Cuneus on touching the nail received a shock. This accidental discovery created the greatest excitement in Europe and America.

61. Residual Charges.—If a Leyden jar be charged and discharged and then left for a little time to itself, it will be found on again discharging that a small second spark can be obtained. There is in fact a residual charge which seems to have soaked into the glass or been absorbed. The return of the residual charge is hastened by tapping the jar. The amount of the residual charge varies with the time that the jar has been left charged; it also depends on the kind of the glass of which the jar is made. There is no residual charge discoverable in an air-leyden after it has once been discharged.

* The honour of the invention of the jar is also claimed for Kleist, Bishop of Pomerania.

62. Batteries of Leyden Jars. — A large Leyden jar will give a more powerful shock than a small one, for a larger charge can be put into it; its capacity is greater. A Leyden jar made of *thin* glass has a greater capacity as a condenser than a thick one of the same size; but if it is too thin it will be destroyed when powerfully charged

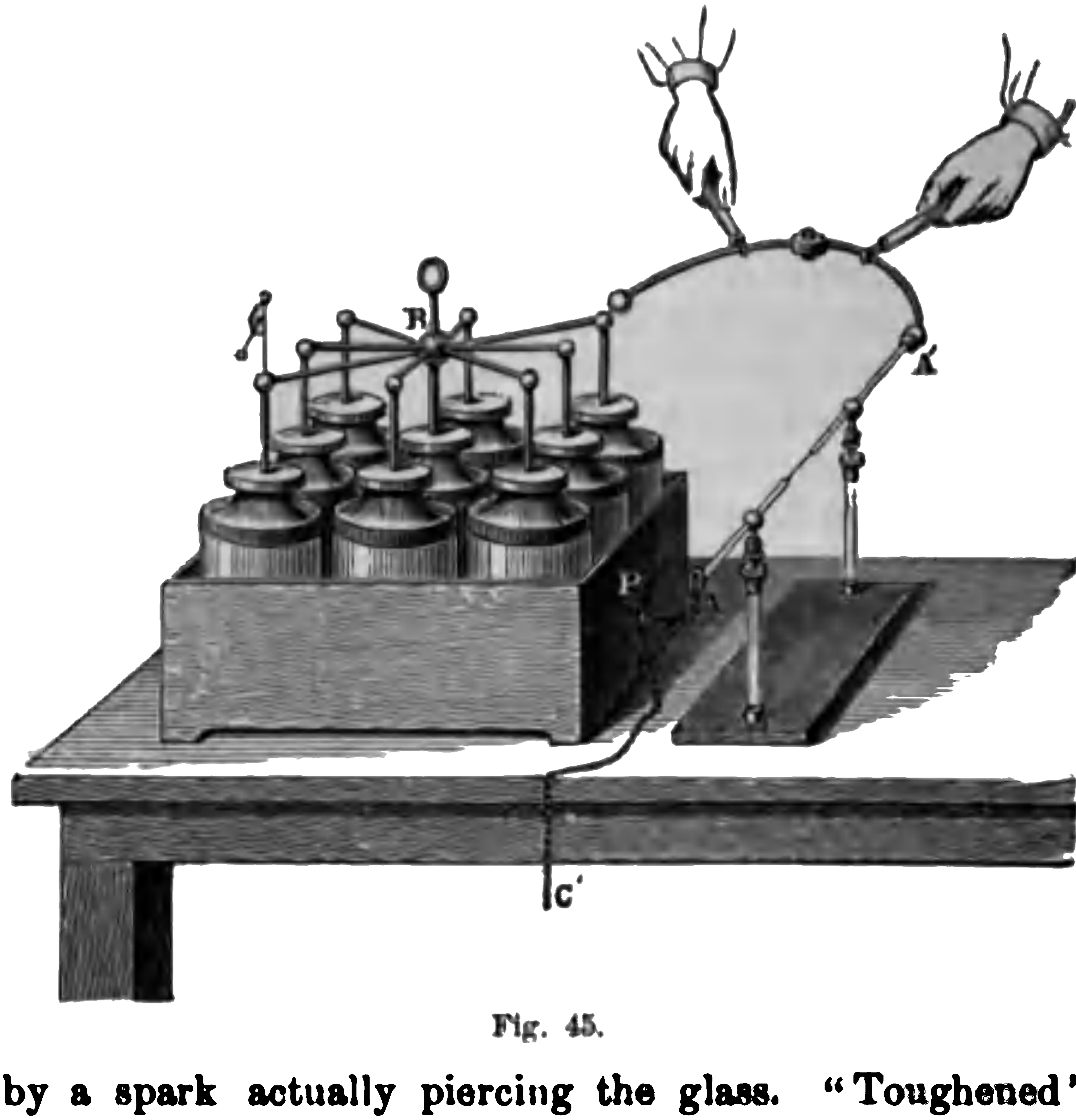


Fig. 45.

by a spark actually piercing the glass. "Toughened" glass is less easily pierced than ordinary glass, and hence Leyden jars made of it may be made thinner, and so will hold a greater charge. To prevent jars from being pierced by a spark, the highest part of the inside coating should be connected across by a strip of foil or a metallic disk to the central wire.

If a jar is desired to give *long sparks*, there must be

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important part in the phenomena. It is now known that all dielectrics across which inductive actions are at work are thereby *strained*.* Inasmuch as a good vacuum is a good dielectric, it is clear that it is not necessarily the material particles of the dielectric substance that are thus affected; hence it is believed that electrical phenomena are due to stresses and strains in the so-called "ether," the thin medium pervading all matter and all space, whose highly elastic constitution enables it to convey to us the vibrations of light though it is millions of times less dense than air. As the particles of bodies are intimately surrounded by ether, the strains of the ether are also communicated to the particles of bodies, and they too suffer a strain. The glass between the two coatings of tinfoil in the Leyden jar is actually strained or squeezed, there being a tension along the lines of electric force. When an insulated charged ball is hung up in a room an equal amount of the opposite kind of charge is attracted to the inside of the walls, and the air between the ball and the walls is strained (electrically) like the glass of the Leyden jar. If a Leyden jar is made of thin glass it may give way under the stress; and when a Leyden jar is discharged the layer of air between the knob of the jar and the knob of the discharging tongs is more and more strained as they are approached towards one another, till at last the stress becomes too great, and the layer of air gives way, and is "perforated" by the spark that discharges itself across. The existence of such stresses enables us to understand the residual charge of Leyden jars in which the glass does not recover itself all at once, by reason of its viscosity, from the strain to which it has been subjected. It must never be forgotten that electric force acts across space in consequence of the transmission of stresses and strains in the

* In the exact sciences a *strain* means an alteration of form or volume due to the application of a stress. A *stress* is the force, pressure, or other agency which produces a strain.

medium with which space is filled. In every case we store not electricity but *energy*. Work is done in pushing electricity from one place to another against the forces which tend to oppose the movement. The charging of a Leyden jar may be likened to the operation of bending a spring, or to pumping up water from a low level to a high one. In charging a jar we pump exactly as much electricity out of the negative side as we pump into the positive side, and we spend energy in so doing. It is this stored energy which afterwards reappears in the discharge.

LESSON VII. — *Other Sources of Electrification*

65. It was remarked at the close of Lesson I. (p. 13) that friction was by no means the only source of electricity. Some of the other sources will now be named.

66. Percussion. — A violent blow struck by one substance upon another produces opposite electrical states on the two surfaces. It is possible indeed to draw up a list resembling that of Art. 6, in such an order that each substance will take a + charge on being struck with one lower on the list.

67. Vibration. — Volpicelli showed that vibrations set up within a rod of metal coated with sulphur or other insulating substance, produced a separation of electricities at the surface separating the metal from the non-conductor.

68. Disruption and Cleavage. — If a card be torn asunder in the dark, sparks are seen, and the separated portions, when tested with an electroscope, will be found to be electrical. The linen faced with paper used in making strong envelopes and for paper collars, shows this very well. Lumps of sugar, crunched in the dark between the teeth, exhibit pale flashes of light. The

sudden cleavage of a sheet of mica also produces sparks, and both laminæ are found to be electrified.

69. **Crystallization and Solidification.**—Many substances, after passing from the liquid to the solid state, exhibit electrical conditions. Sulphur fused in a glass dish and allowed to cool is violently electrified, as may be seen by lifting out the crystalline mass with a glass rod. Chocolate also becomes electrical during solidification. When arsenic acid crystallizes out from its solution in hydrochloric acid, the formation of each crystal is accompanied by a flash of light, doubtless due to an electrical discharge. A curious case occurs when the sulphate of copper and potassium is fused in a crucible. It solidifies without becoming electrical, but on cooling a little further the crystalline mass begins to fly to powder with an instant evolution of electricity.

70. **Combustion.**—Volta showed that combustion generated electricity. A piece of burning charcoal, or a burning pastille, such as is used for fumigation, placed in connexion with the knob of a gold-leaf electroscope, will cause the leaves to diverge.

71. **Evaporation.**—The evaporation of liquids is often accompanied by electrification, the liquid and the vapour assuming opposite states, though apparently only when the surface is in agitation. A few drops of a solution of sulphate of copper thrown into a hot platinum crucible produce violent electrification as they evaporate.

72. **Atmospheric Electricity.**—The atmosphere is found to be always electrified relatively to the earth: this is due, in part possibly, to evaporation going on over the oceans. The subject of atmospheric electricity is treated of separately in Lesson XXV.

73. **Pressure.**—A large number of substances when compressed exhibit electrification on their surface. Thus cork becomes + when pressed against amber, gutta-percha, and metals; while it takes a – charge when

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steady no such electrical effects are observed either at high or low temperatures; and the phenomena cease if the crystal be warmed above 150° C. This is not, however, due to the crystal becoming a conductor at that temperature; for its resistance at even higher temperatures is still so great as to make it practically a non-conductor. A heated crystal of tourmaline suspended by a silk fibre may be attracted and repelled by electrified bodies, or by a second heated tourmaline; the two similar poles repelling one another, while the two poles

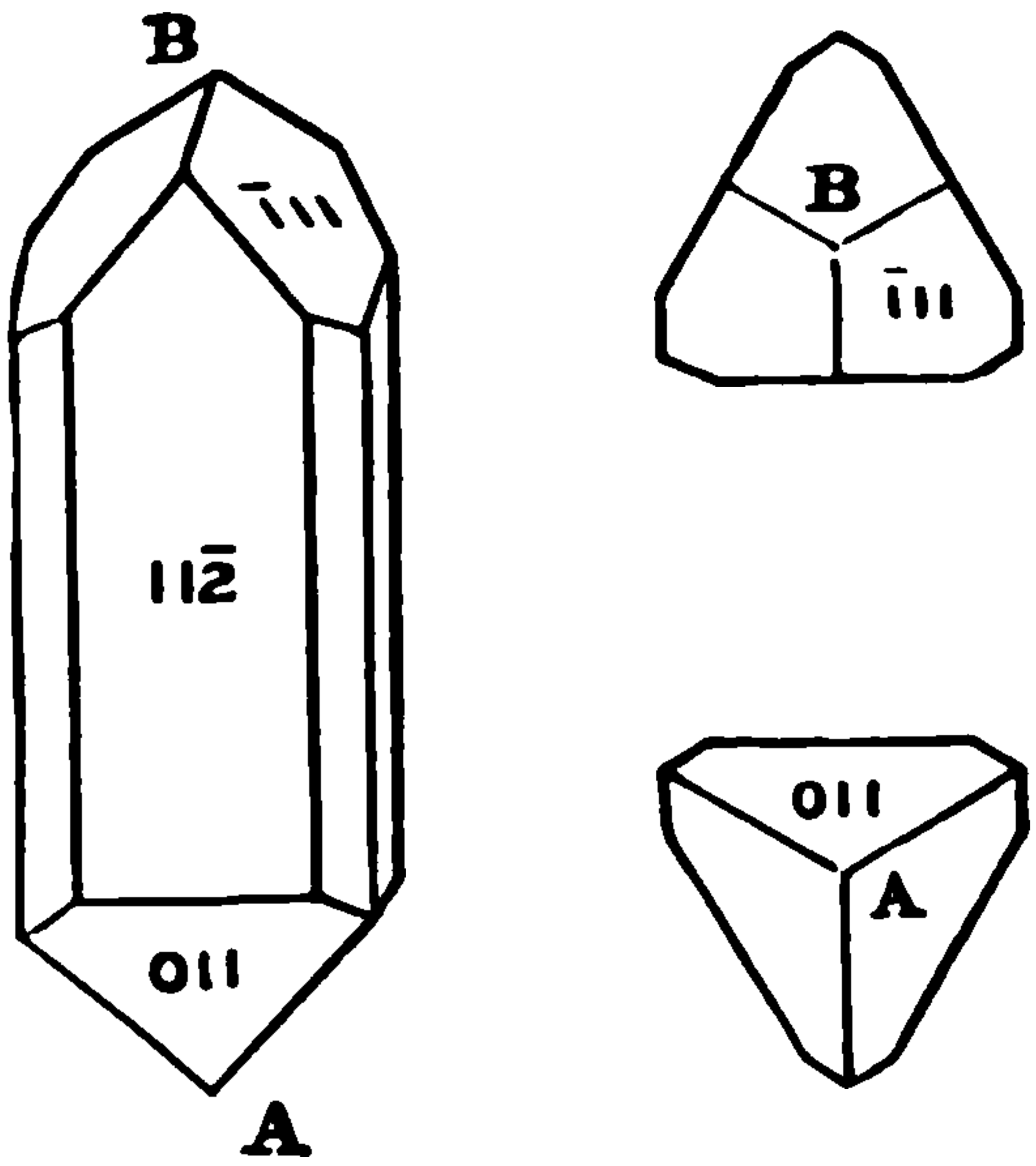


Fig. 47.

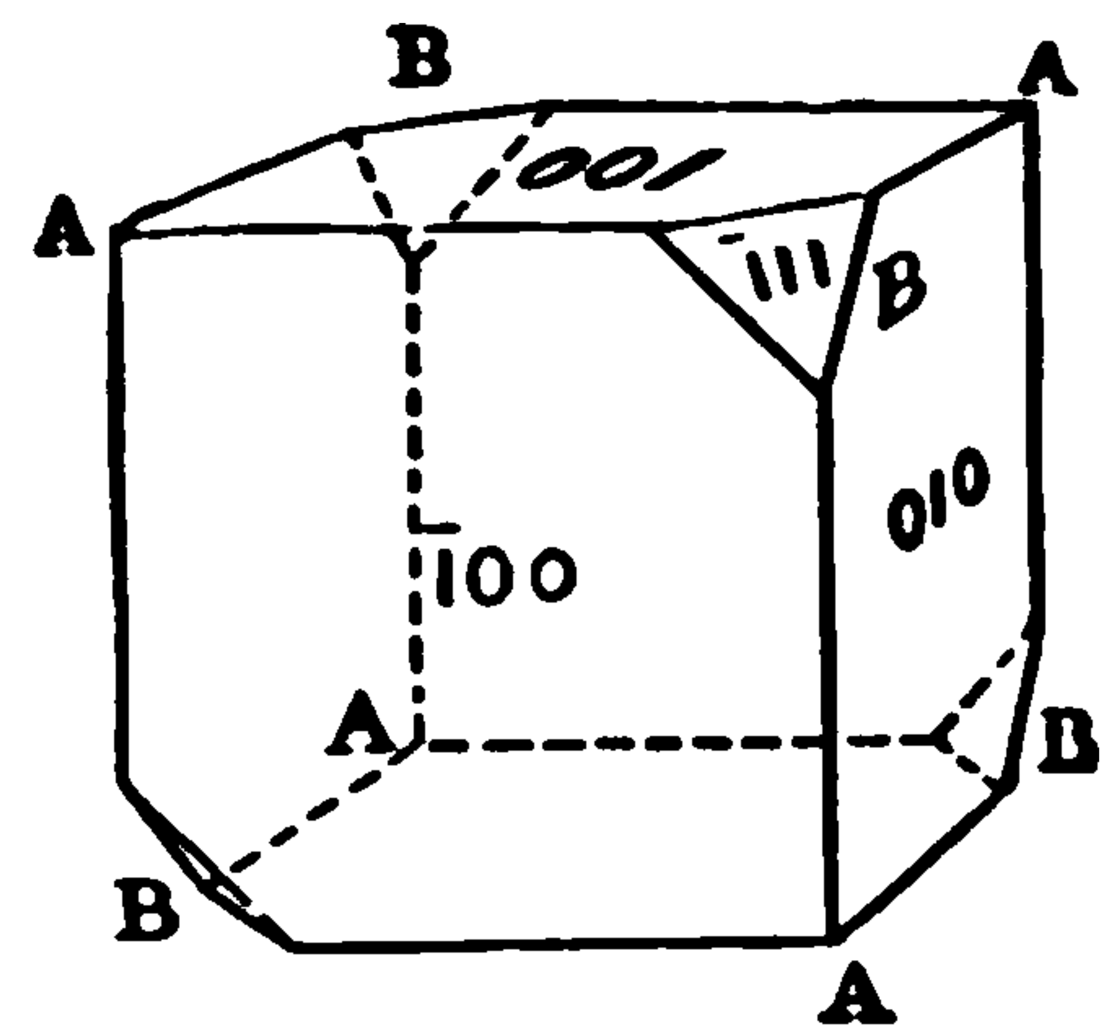


Fig. 48.

of opposite form attract one another. If a crystal be broken up, each fragment is found to possess also an analogous and an antilogous pole.

Many other crystals beside the tourmaline are more or less pyro-electric. Amongst these are silicate of zinc ("electric calamine"), boracite, cane-sugar, quartz, tartrate of potash, sulphate of quinine, and several others. *Boracite* crystallizes in the form shown in Fig. 48, which represents a cube having four alternate corners truncated. The corners not truncated behave as analogous poles, the truncated ones as antilogous. When a natural hexagonal prism of quartz is heated its six edges are found to be + and − in alternate order.

75. Piezo-electricity.—In certain crystals pressure in a particular direction may produce electrification. Haüy found that a crystal of calcspar pressed between the dry fingers, so as to compress it along the blunt edges of the crystal, became electrical, and that it retained its electricity for some days. He even proposed to employ a squeezed suspended crystal as an electroscope. A similar property is alleged of mica, topaz, and fluorspar. If two opposite edges of a hexagonal prism of quartz are pressed together, one becomes +, the other −. Pressure also produces opposite kinds of electrification at opposite ends of a crystal of tourmaline, and of other crystals of the class already noticed as possessing the peculiarity of skew-symmetry or hemihedry in their structure. *Piezo-electricity* is the name given to this branch of the science. It is known that skew-symmetry of structure is dependent on molecular constitution; and it is doubtless the same peculiarity which determines the pyro-electric and piezo-electric properties, as well as the optical behaviour of these crystals in polarized light.

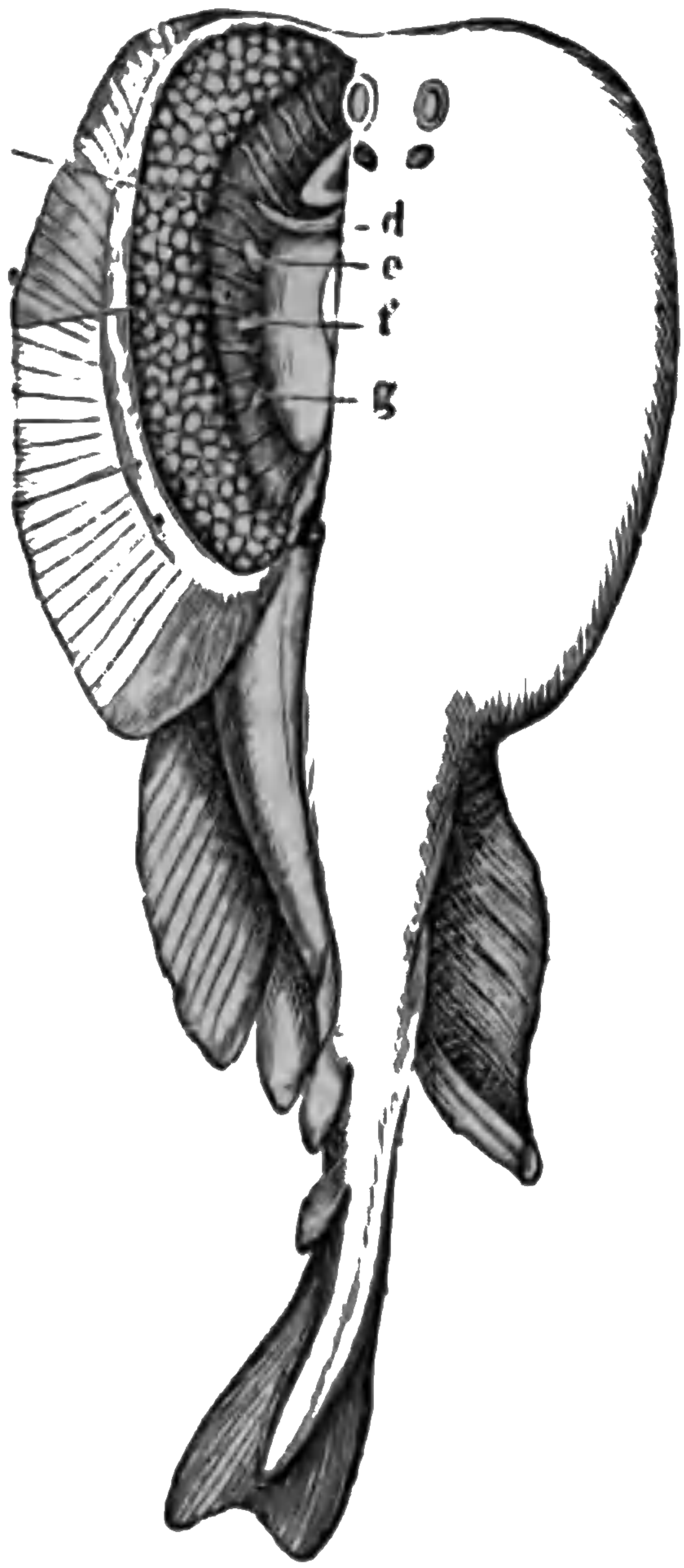


Fig. 49.

76. Animal Electricity.—Several species of creatures inhabiting the water have the power of producing electric discharges physiologically. The best known of these creatures are the *Torpedo*, the *Gymnotus*, and the

Silurus. The **Raia Torpedo**,* or electric ray, of which there are three species inhabiting the Mediterranean and Atlantic, is provided with an electric organ on the back of its head, as shown in Fig. 49. This organ consists of laminæ composed of polygonal cells to the number of 800 or 1000, or more, supplied with four large bundles of nerve fibres; the under surface of the fish is –, the upper +. In the **Gymnotus electricus**, or Surinam eel (Fig. 50), the electric organ goes the whole length of the body from tail to head. Humboldt gives a lively account of the



Fig. 50.

combats between the electric eels and the wild horses, driven by the natives into the swamps inhabited by the Gymnotus. It is able to give a most terrible shock, and is a formidable antagonist when it has attained its full length of 5 or 6 feet. In the **Silurus** the current flows from head to tail.

Nobili, Matteucci, and others, have shown that nerve-excitations and muscular contractions of human beings also give rise to feeble discharges of electricity.

77. Electricity of Vegetables.—Buff thought he detected electrification produced by plant life; the roots and juicy parts being negatively, and the leaves positively, electrified. The subject has, however, been little investigated.

* It is a curious point that the Arabian name for the torpedo, *ra ad*, signifies *lightning*. This is perhaps not so curious as that the *Electra* of the Homeric legends should possess certain qualities that would tend to suggest that she is a personification of the *lightning*. The resemblance between the names *electra* and *electron* (amber) cannot be accidental.

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densing electroscope that contact of dissimilar metals does produce electrification, a small compound bar made of two dissimilar metals — say zinc and copper — soldered together, is held in the moist hand, and one end of it is touched against the lower plate, the upper plate being placed in contact with the ground or touched with the finger. When the two opposing charges have thus collected in the condenser the upper plate is removed, and the diverging of the gold leaves shows the presence of a free charge, which can afterwards be examined to see whether it be + or −. Instead of employing the copper-zinc bar, a single voltaic cell may be connected by copper wires to the two plates. For a long time the existence of this electrification by contact was denied, or rather it was declared to be due (when occurring in voltaic combinations such as are described in Lesson XIII.) to chemical actions going on; whereas the real truth is that the electricity of contact and the chemical action are both due to molecular conditions of the substances which come into contact with one another, though we do not yet know the precise nature of the molecular conditions which give rise to these two effects. Later experiments, especially those made with the modern delicate electrometers of Lord Kelvin, put beyond doubt the reality of Volta's discovery. One simple experiment explains the method adopted. A thin strip or needle of metal is suspended so as to turn about a point *C*. It is electrified from a known source. Under it are placed (Fig. 52) two semicircular disks, or half-rings of dissimilar

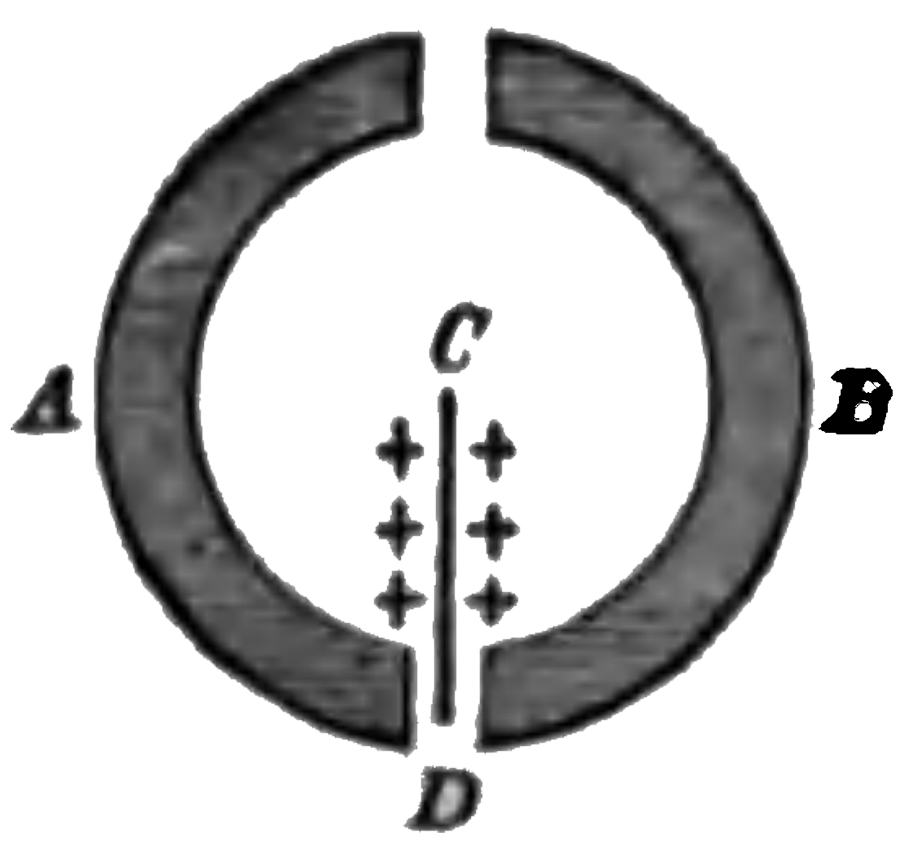


Fig. 52.

becomes "free" when the top plate is lifted up; the above is, however, a more scientific and more accurate way of saying the same thing. The student who is unable to reconcile these two ways of stating the matter should read again Articles 40 and 55, on pp. 46 and 68. A much more sensitive apparatus to show the effect is the quadrant electrometer (Art. 288).

metals. Neither attracts or repels the electrified needle until the two are brought into contact, or connected by a third piece of metal, when the needle immediately turns, being attracted by the one that is oppositely electrified, and repelled by the one that is electrified similarly with itself.

80. Contact Series of Metals (in Air). — Volta found, moreover, that the differences of electric potential between the different pairs of metals were not all equal. Thus, while zinc and lead were respectively + and – to a slight degree, he found zinc and silver to be respectively + and – to a much greater degree. He was able to arrange the metals in a series such that each one enumerated became positively electrified when placed in contact in air with one below it in the series. Those in italics are added from observations made since Volta's time —

\+ *Sodium*,
Magnesium,
Zinc,
Lead,
Tin,
Iron,
Copper,
Silver,
Gold,
Platinum,
– *Graphite* (Carbon).

Though Volta gave rough approximations, the actual numerical values of the differences of potential in air for different pairs of metals have only lately been measured by Ayrton and Perry, a few of whose results are tabulated here —

	Difference of Potential (volts).
Zinc	
	·210
Lead	
	·069
Tin	
	·313
Iron	
	·146
Copper	
	·238
Platinum	
	·113
Carbon	

The difference of potential between zinc and carbon is the same as that obtained by adding the successive differences, or 1·09 volts.* Volta's observations may therefore be stated in the following generalized form, known as **Volta's Law**. *The difference of potential between any two metals is equal to the sum of the differences of potentials between the intervening metals in the contact-series.*

It is most important to notice that the order of the metals in the contact-series *in air* is almost identical with that of the metals arranged according to their electro-chemical power, as calculated from their chemical equivalents and their heat of combination with oxygen (see Table, Art. 489). From this it would appear that the difference of potentials between a metal and the air that surrounds it measures the tendency of that metal to become oxidized by the air. If this is so, and if (as is the case) the air is a bad conductor while the metals are good conductors, it ought to follow that when two different metals touch they equalize their own potentials by conduction but leave the films of air that surround them at different potentials. All the exact experiments yet made have measured the difference of potentials not between the metals themselves, but between the air near one metal and that near another metal. It is certain that while in air iron is positive to copper, but in an atmosphere of sulphuretted hydrogen, iron is negative to copper. Mr. John Brown has lately demonstrated the existence on freshly-cleaned metal surfaces of *films* of liquid or condensed gases, and has shown that polished zinc and copper, when brought so near that their films touch, will act as a battery.

81. Contact Actions. — A difference of potential is also produced by the contact of *two dissimilar liquids* with one another.

* For the definition of the *volt*, or unit of difference of potential, see Art. 254.

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different forces. There are (see Art. 10) good reasons for thinking that the electricity of friction is really due to electricity of contact, excited at successive portions of the surfaces as they are moved over one another. But of the molecular conditions of bodies which determine the production of electrification where they come into contact, little or nothing is yet known.

CHAPTER II

MAGNETISM

Lesson VIII. — *Magnetic Attraction and Repulsion*

84. Lodestones or Natural Magnets. — The name **Magnet** (*Magnes Lapis*) was given by the ancients to certain hard black stones found in various parts of the world, notably at *Magnesia* in Asia Minor, which possessed the property of attracting to them small pieces of iron. This magic property, as they deemed it, made the magnet-stone famous; but it was not until the tenth or twelfth century that such stones were discovered to have the still more remarkable property of pointing north and south when hung up by a thread. This property was turned to advantage in navigation, and from that time the magnet received the name of **Lodestone** * (or "leading-stone"). The natural magnet or lodestone is an ore of iron, known to mineralogists as *magnetite* and having the chemical composition Fe_3O_4. This ore is found in quantities in Sweden, Spain, the Isle of Elba, Arkansas, and other parts of the world, though not always in the magnetic condition. It frequently occurs in crystals; the usual form being the regular octahedron.

85. Artificial Magnets. — If a piece of hard iron be rubbed with a lodestone, it will be found to have also

* The common spelling *load*stone is due to misapprehension.

acquired the properties characteristic of the stone; it will attract light bits of iron, and if hung up by a thread it will point north and south. Savery, in 1729, first showed how much more retentive of magnetism hardened steel is than mere iron. Figs. 53 and 54 represent a natural lodestone and an artificial magnet of steel, each of which has been dipped into iron-filings; the filings are attracted and adhere in tufts.



Figs. 53 and 54.

86. Writings of Dr. Gilbert. — This was all, or nearly all, that was known of the magnet until 1600, when Dr. Gilbert published a large number of magnetic discoveries in his famous work *De Magnete*. He observed that the attractive power of a magnet appears to reside at two regions, and in a long-shaped magnet these regions, or **poles**, are usually at the ends (see Figs. 53 and 54). The portion of the magnet which lies between the two poles is apparently less magnetic, and does not attract iron-filings so strongly; and all round the magnet, halfway between the poles, there is no attraction at all. This region Gilbert called the **equator** of the magnet, and the imaginary line joining the poles he termed the **axis**.

87. Magnetic Needle. — To investigate more fully the magnetic forces a **magnetic needle** is employed. This consists (Fig. 55) of a light needle cut out of steel, and fitted with a little cap of brass, glass, or agate, by means of which it can be hung upon a sharp point, so as to turn with very little friction. It is rendered magnetic by being rubbed upon a magnet; and when thus magnetized it will turn into the north-and-south

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which has previously been suspended, and which has its north-pointing end *marked* to distinguish it from the south-pointing end, we shall discover that the N-pointing pole repels the N-pointing pole, and that the S-pointing pole repels the S-pointing pole; but that a N-pointing pole attracts and is attracted by a S-pointing pole.

89. Two Kinds of Magnetic Poles.—There would therefore appear to be two opposite kinds of magnetism, or at any rate two opposite kinds of magnetic poles, which attract or repel one another in very much the same fashion as the two opposite kinds of electrification do; and one of these kinds of magnetism appears to have a tendency to move toward the north and the other to move toward the south. It has been proposed to call these two kinds of magnetism "north-seeking magnetism" and "south-seeking magnetism," but for our purpose it is sufficient to distinguish between the two kinds of poles. In common parlance the poles of a magnet are called the "North Pole" and "South Pole" respectively, and it is usual for the makers of magnets to mark the N-pointing pole with a letter N. It is therefore sometimes called the "marked" pole, to distinguish it from the S-pointing or "unmarked" pole. We shall, to avoid any doubt,* call that pole of a magnet which would,

* It is necessary to be precise on this point, as there is some confusion in the existing text-books. The cause of the confusion is this:—If the north-pointing pole of a needle is *attracted* by magnetism residing near the North Pole of the earth, the law of attraction (that *unlike poles attract*) shows us that these two poles are really magnetically of opposite kinds. Which are we then to call north magnetism? That which is at the N pole of the earth? If so, we must say that the N-pointing pole of the needle contains south magnetism. And if we call that north magnetism which points to the north, then we must suppose the magnetic pole at the north pole of the earth to have south magnetism in it. In either case there is then a difficulty. The Chinese and the French call the N-pointing pole of the needle a south pole, and the S-pointing pole a north pole. Lord Kelvin also calls the N-pointing pole a "True South" pole. But common practice goes the other way, and calls the N-pointing pole of a magnet its "North" pole. For experimental purposes it is usual to paint the two poles of a magnet of different colours, the N-seeking pole being coloured

if the magnet were suspended, tend to turn to the north, the "North-seeking" pole, and the other the "South-seeking" pole.

We may therefore sum up our observations in the concise statement: *Like magnetic poles repel one another; unlike poles attract one another.* This we may call the first law of magnetism. As with the electric attractions and repulsions of rubbed bodies, so with these magnetic attractions and repulsions the effects are due, as we shall see, to stresses in the intervening medium.

90. The two Poles inseparable. — It is impossible to obtain a magnet with only one pole. If we magnetize a piece of steel wire, or watch spring, by rubbing it with one pole of a magnet, we shall find that still it has two poles — one N-seeking, the other S-seeking. And if we break it into two parts, each part will still have two poles of opposite kinds.

91. Magnetic Force. — The force with which a magnet attracts or repels another magnet, or any piece of iron or steel, we shall call *magnetic force.** The force exerted by a magnet upon a bit of iron or on another magnet is not the same at all distances, the force being greater when the magnet is nearer, and less when the magnet is farther off. (See Art. 128, on laws of magnetic force.)

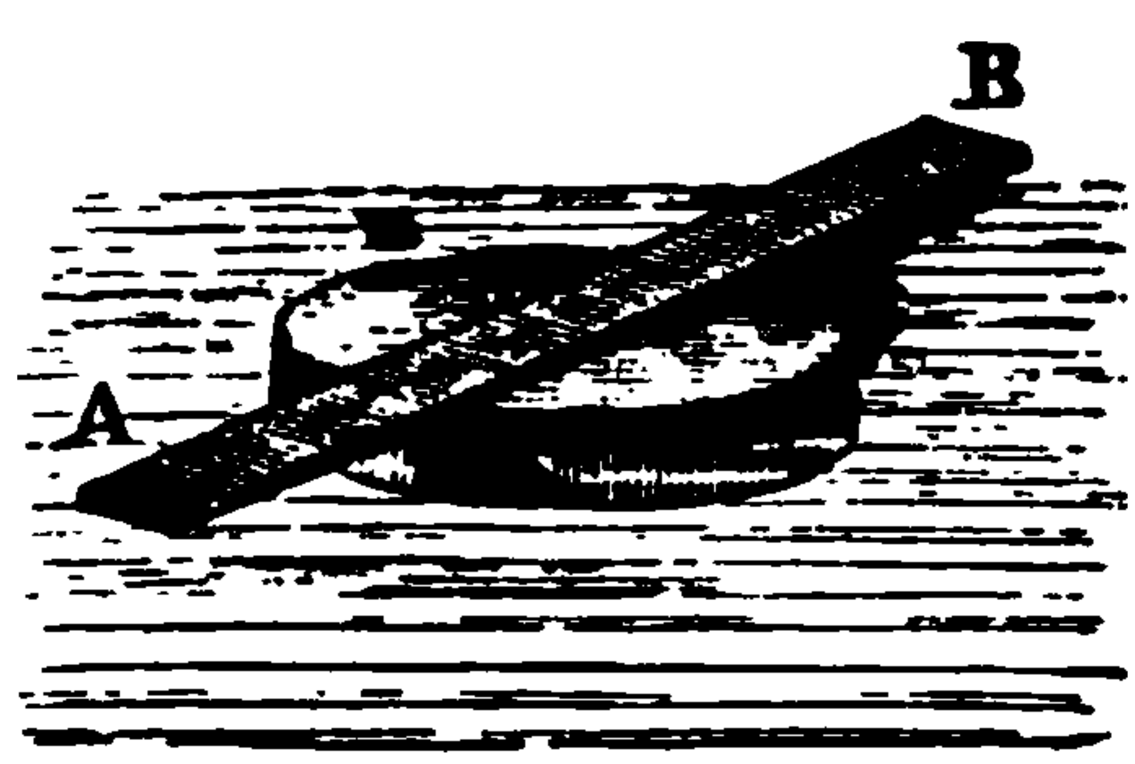


Fig. 57.

Whenever a force acts thus between two bodies, it acts on both of them, tending to move both. A magnet will attract a piece of iron, and a piece of iron will attract a magnet. This was shown by Sir Isaac Newton, who

red and the S-seeking pole *blue;* but here again, strangely enough, authorities differ, for in the collections of apparatus at the Royal Institution and Royal School of Mines, the colours are used in exactly the opposite way to this, which is due to Airy.

* See footnote on "Force," Art. 169.

fixed a magnet upon a piece of cork and floated it in a basin of water (Fig. 57), and found that it moved across the basin when a piece of iron was held near. A compass needle thus floated turns round and points north and south; but it does not rush towards the north as a whole, nor towards the south. The reason of this will be explained later, in Art. 129.

Gilbert suggested that the force of a magnet might be measured by making it attract a piece of iron hung to one arm of a balance, weights being placed in the scale-pan hanging to the other arm; and he found, by hanging the *magnet* to the balance and placing the *iron* beneath it, that the effect produced was the same. The action and reaction are then equal for magnetic forces.

92. Magnetic Substances. — A distinction was drawn by Gilbert between *magnets* and *magnetic substances.* A magnet attracts only at its poles, and they possess opposite properties. But a lump of iron will attract either pole of the magnet, no matter what part of the lump be presented to the magnet. It has no distinguishable fixed "poles," and no magnetic "equator." A true magnet has poles, one of which is *repelled* by the pole of another magnet.

93. Other Magnetic Metals. — Later experimenters have extended the list of substances which are attracted by a magnet. In addition to iron (and steel) the following metals are recognized as magnetic: —

Nickel.	Chromium.
Cobalt.	Cerium,

and a few others. But only nickel and cobalt are at all comparable with iron and steel in magnetic power, and even they are very far inferior. Other bodies, sundry salts of iron and other metals, paper, porcelain, and oxygen gas, are also very feebly attracted by a powerful magnet.

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an electrified one. The analogy, indeed, goes further than this, for it is found that the iron bar thus magnetized by induction will have two poles; the pole nearest to the pole of the inducing magnet being of the opposite kind, while the pole at the farther end of the bar is of the same kind as the inducing pole. Those bodies in which a magnetizing force produces a high degree of magnetization are said to possess a high *permeability*. It will be shown presently that magnetic induction takes place along certain directions called *lines of magnetic induction*, or *lines of magnetic force*, which may pass either through iron and other magnetic media, or through air, vacuum, glass, or other non-magnetic media: and, since induction goes on most freely in bodies of high magnetic permeability, the magnetic lines are sometimes (though not too accurately) said to "pass by preference through magnetic matter," or, that "magnetic matter conducts the lines of force."

97. Attraction across Bodies.—If a sheet of glass, or wood, or paper, be interposed between a magnet and the piece of iron or steel it is attracting, it will still attract it as if nothing were interposed. A magnet sealed up in a glass tube still acts as a magnet. Lucretius found a magnet put into a brass vase attracted iron filings through the brass. Gilbert surrounded a magnet by a ring of flames, and found it still to be subject to magnetic attraction from without. Across water, vacuum, and all known substances, the magnetic forces will act; with the single apparent exception, however, that magnetic force will not act across a *screen of iron* or other magnetic material, if sufficiently thick. If a small magnet is suspended inside a hollow ball made of iron, no outside magnet will affect it. The reason being that the magnetic lines of force are conducted off laterally through the iron instead of penetrating through it. A hollow shell of iron will therefore act as a *magnetic cage*, and shield the space inside it from magnetic influences.

Fig. 59 illustrates the way in which a cylinder of soft iron shields the space interior to it from the influence of an external magnet. A compass needle placed at P inside the cylinder is not affected by the presence of the magnet outside, for its lines of magnetic force are drawn off laterally. Similarly a magnet inside is shielded from affecting outside space.

Although magnetic induction takes place at a distance across an intervening layer of air, glass, or vacuum, there is no doubt that the intervening medium is directly concerned in the transmission of the magnetic force, though the true medium is probably the "ether" of space sur-

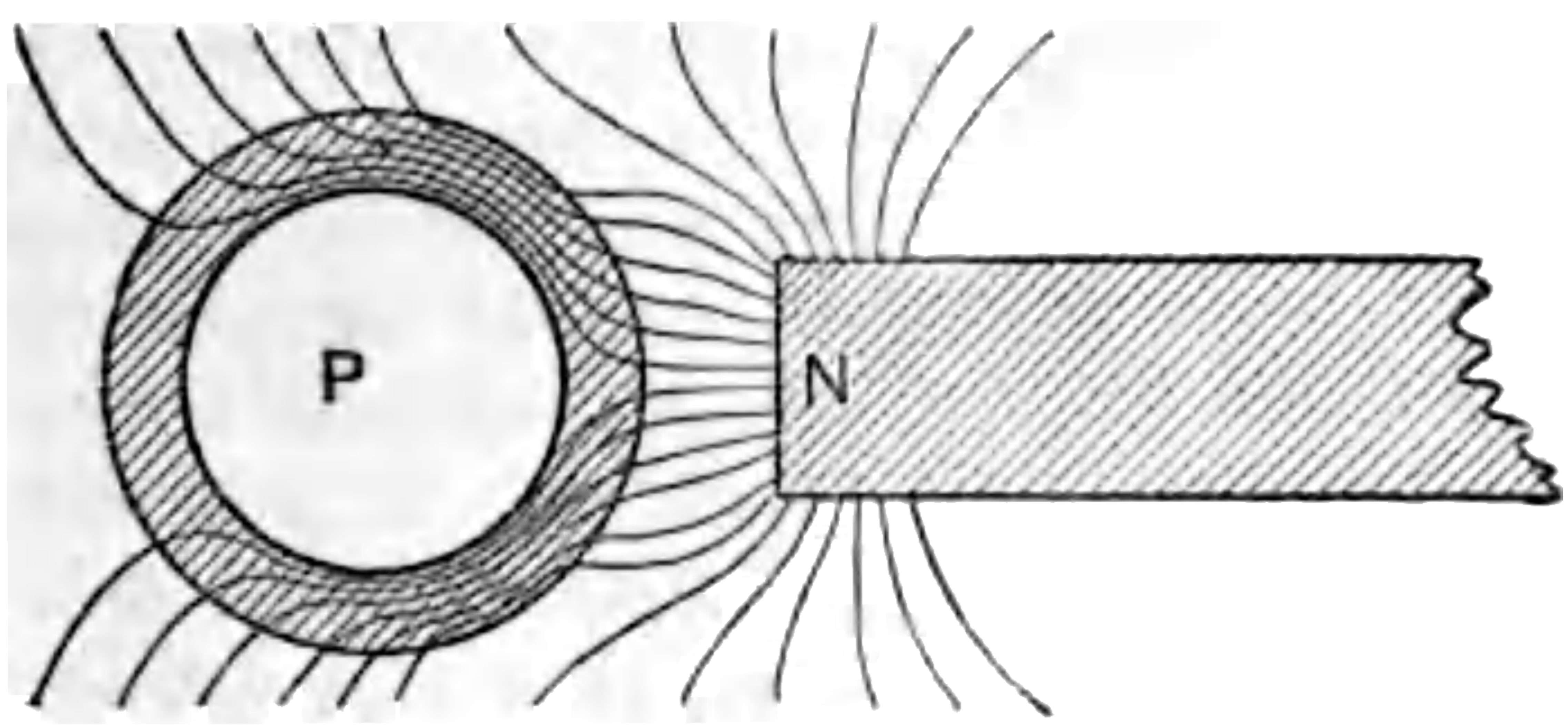


Fig. 59.

rounding the molecules of matter, not the molecules themselves.

We now can see why a magnet should attract a not-previously-magnetized piece of iron; it first magnetizes it by induction and then attracts it: for the nearest end will have the opposite kind of magnetism induced in it, and will be attracted with a force exceeding that with which the more distant end is repelled. But *induction precedes attraction.*

98. Retention of Magnetization.—Not all magnetic substances can become magnets permanently. Lodestone, steel, and nickel retain permanently the great part of the magnetism imparted to them. Cast iron and many impure qualities of wrought iron also retain

which has previously been suspended, and which has its north-pointing end *marked* to distinguish it from the south-pointing end, we shall discover that the N-pointing pole repels the N-pointing pole, and that the S-pointing pole repels the S-pointing pole; but that a N-pointing pole attracts and is attracted by a S-pointing pole.

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Nickel.	Chromium.
Cobalt.	Cerium,

and a few others. But only nickel and cobalt are at all comparable with iron and steel in magnetic power, and even they are very far inferior. Other bodies, sundry salts of iron and other metals, paper, porcelain, and oxygen gas, are also very feebly attracted by a powerful magnet.

94. Diamagnetism. — A number of bodies, notably bismuth, antimony, phosphorus, and copper, are apparently repelled from the poles of a magnet. Such bodies are called *diamagnetic bodies;* a fuller account of them will be found in Lesson XXIX.

95. The Earth a Magnet. — The greatest of Gilbert's discoveries was that of the inherent magnetism of the earth. *The earth is itself a great magnet,* whose "poles" coincide nearly, but not quite, with the geographical north and south poles, and therefore it causes a freely-suspended magnet to turn into a north-and-south position. Gilbert had some lodestones cut to the shape of spheres to serve as models of the globe of the earth. Such a globular magnet he called a *terrella.* He found that small magnets turned toward the poles of the terrella, and dip, as compass-needles do, toward the earth.

The subject of *Terrestrial Magnetism* is treated of in Lesson XII. It is evident from the first law of magnetism that the magnetic condition of the northern regions of the earth must be the opposite to that of the north-seeking pole of a magnetized needle. Hence arises the difficulty alluded to on page 92.

96. Induction of Magnetism. — Magnetism may be communicated to a piece of iron without actual contact



Fig. 58.

with a magnet. If a short, thin unmagnetized bar of iron be placed near some iron filings, and a magnet be brought near to the bar, the presence of the magnet will *induce* magnetism in the iron bar, and it will now attract the iron filings (Fig. 58). This inductive action is very similar to that observed in Lesson III. to take place when a non-electrified body was brought under the influence of

[illegible] further [illegible] this magnet- [illegible] the nearest [illegible] opposite [illegible] the air is [illegible] Those other [illegible] degree of [illegible] *permeability*. It [illegible] induction takes [illegible] a *magnetic* [illegible] may take either [illegible] through air, [illegible] and, since [illegible] magnetic [illegible] sometimes through [illegible] preference through [illegible] magnetic matter conducts [illegible]

37. Attraction across Bodies. — [illegible] sheet of glass [illegible] between a magnet and the [illegible] it is attracting, it will still at- [illegible] interposed. A magnet sealed [illegible] as a magnet. Lucretius found [illegible] attracted iron filings [illegible] Gilbert surrounded a magnet by a [illegible] and found it still to be subject to magnetic [illegible] Across water, vacuum, and all [illegible] the magnetic forces will act; with the [illegible] however, that magnetic force [illegible] or other magnetic [illegible] If a small magnet is sus- [illegible] made of iron, no outside [illegible] The reason being that the mag- [illegible] are conducted off laterally through [illegible] penetrating through it. A hollow [illegible] therefore act as a *magnetic cage*, and [illegible] inside it from magnetic influences.

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magnetism imperfectly. The softer and purer a specimen of iron is, the more lightly is its residual magnetism retained. The following experiment illustrates the matter:—Let a few pieces of iron rod, or a few soft iron nails be taken. If one of these (see Fig. 60) be placed in contact with the pole of a permanent steel magnet, it is attracted to it, and becomes itself a temporary magnet. Another bit of iron may then be hung to it, and another, until a chain of four or five pieces is built up. But if the steel magnet be removed from the top of the chain, all the rest drop off, and are found to be no longer magnetic. A similar chain of steel needles may be formed, but they will retain permanently most of their magnetism.

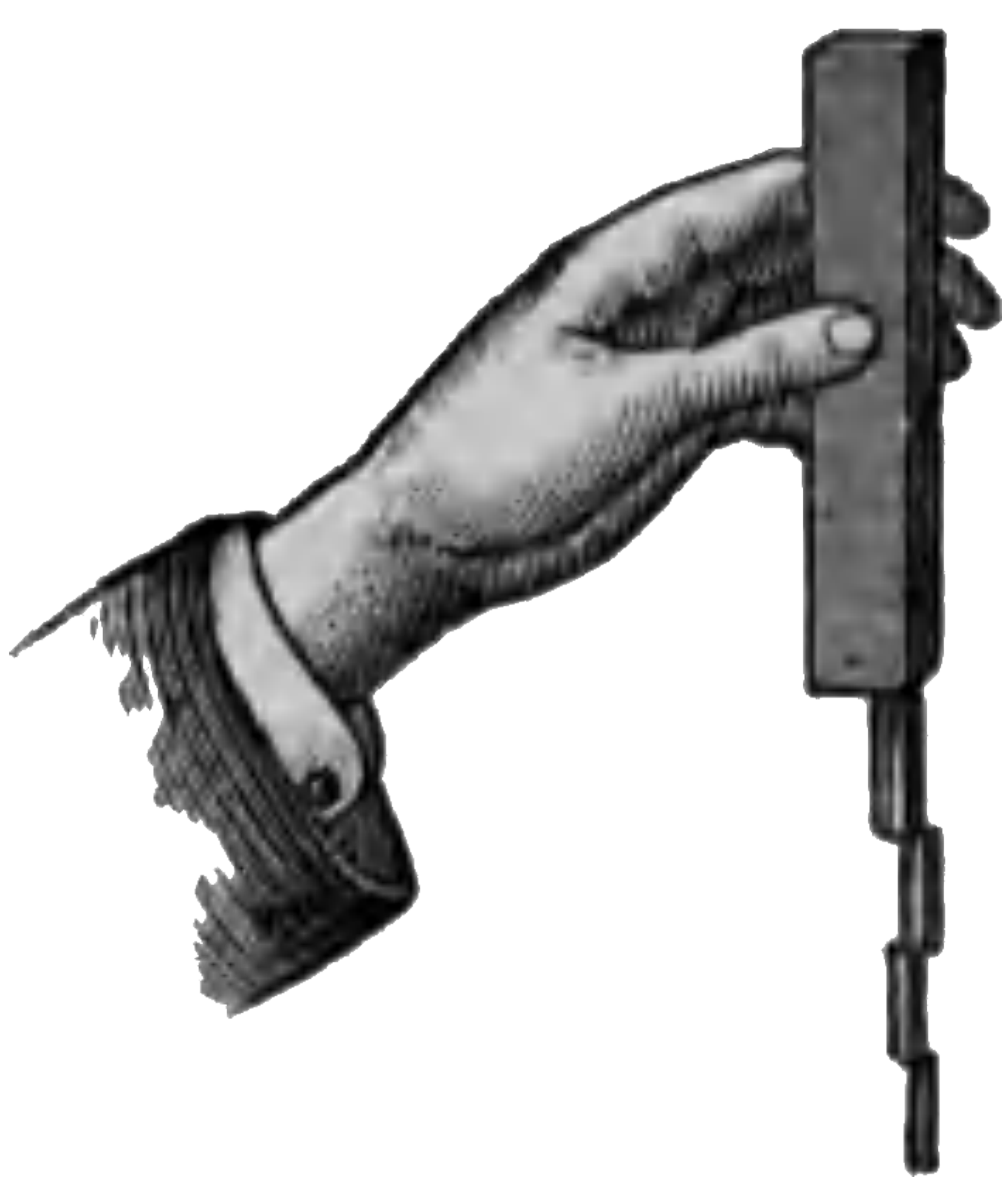


Fig. 60.

It will be found, however, that a steel needle is more difficult to magnetize than an iron needle of the same dimensions. It is harder to get the magnetism *into* steel than into iron, and it is harder to get the magnetism *out* of steel than out of iron; for the steel retains the magnetism once put into it. This power of resisting magnetization, or demagnetization, is sometimes called *coercive force;* a much better term, due to Lamont, is **retentivity**. The retentivity of hard-tempered steel is great; that of soft wrought iron is very small. The harder the steel, the greater its retentivity. Form affects retentivity. Elongated forms and those shaped as closed or nearly closed circuits retain their magnetism better than short rods, balls, or cubes.

99. Theories of Magnetism.—The student will not have failed to observe the striking analogies between the phenomena of attraction, repulsion, induction, etc., of magnetism and those of electricity. Yet the two sets

of phenomena are quite distinct. A positively electrified body does not attract either the North-pointing or the South-pointing pole of the magnet as such; in fact, it attracts either pole quite irrespective of its magnetism, just as it will attract any other body. There does exist, indeed, a direct relation between magnets and *currents* of electricity, as will be later explained. There is none known, however, between magnets and stationary *charges* of electricity.

In many treatises it is the fashion to speak of a magnetic fluid or fluids; it is, however, *absolutely certain that magnetism is not a fluid*, whatever else it may be. The term is a relic of bygone times. A magnet when rubbed upon a piece of steel magnetizes it *without giving up or losing any of its own magnetism*. A fluid cannot possibly propagate itself indefinitely without loss. The arguments to be derived from the behaviour of a magnet on breaking, and from other experiments narrated in Lesson X., are even stronger. No theory of magnetism will therefore be propounded until these facts have been placed before the student.

LESSON IX. — *Methods of making Magnets*

100. Magnetization by Single Touch. — It has been so far assumed that bars or needles of steel were to be magnetized by simply touching them, or stroking them from end to end with the pole of a permanent magnet of lodestone or steel. In this case the last touched point of the bar will be a pole of opposite kind to that used to touch it; and a more certain effect is produced if one pole of the magnet be rubbed on one end of the steel needle, and the other pole upon the other end. There are, however, better ways of magnetizing a bar or needle.

101. Magnetization by Divided Touch. — In this method the bar to be magnetized is laid down hori-

zontally; two bar magnets are then placed down upon it, their opposite poles being together. They are then drawn asunder from the middle of the bar towards its ends, and back, several times. The bar is then turned over, and the operation repeated, taking care to leave off at the middle (see Fig. 61). The process is more effectual if the ends of the bar are meantime supported on the poles of other bar magnets, the poles being of the same names as those of the two magnets above them used for stroking the steel bar.

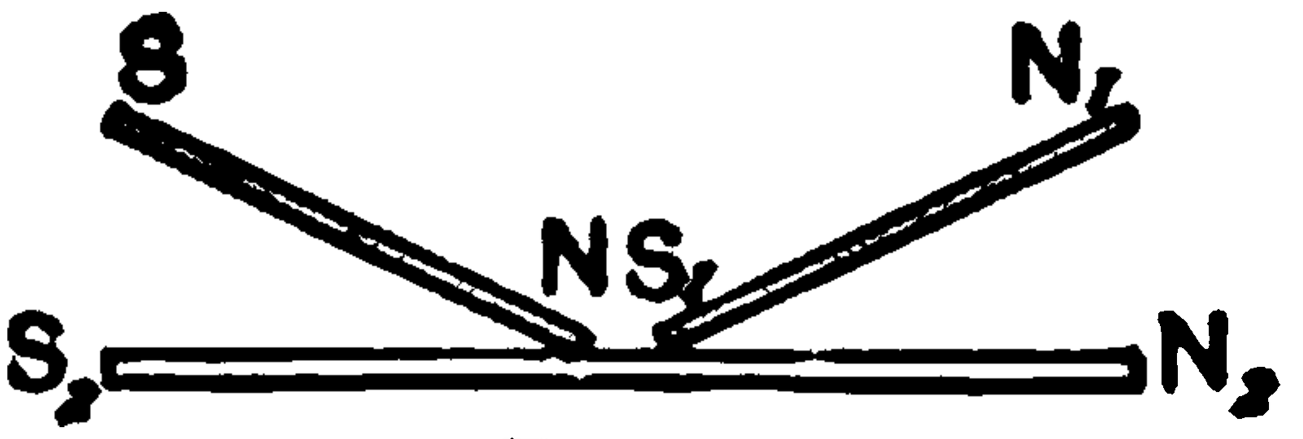


Fig. 61.

102. **Magnetization by Double Touch.** — Another method, known as *double touch*, differs slightly from that last described. A piece of wood or cork is interposed between the ends of the two bar magnets employed, and they are then both moved backwards and forwards along the bar that is to be magnetized. By none of these methods, however, can a steel bar be magnetized beyond a certain degree of intensity.

103. **Forms of Magnets.** — Natural magnets are usually of irregular form, though they are sometimes reduced to regular shapes by cutting or grinding. Formerly it was the fashion to mount them with soft iron cheeks or "armatures" to serve as pole-pieces.

For scientific experiments *bar magnets* of hardened steel are commonly used; but for many purposes the *horse-shoe* shape is preferred. In the horse-shoe magnet the poles are bent round so as to approach one another, the advantage here being that so both poles can attract one piece of iron. The "armature," or "keeper," as the piece of soft iron placed across the poles is named, is itself rendered a magnet by induction when placed across the poles; hence, when *both* poles magnetize it, the force with which it is attracted to the magnet is the greater.

104. **Laminated Magnets.** — It is found that long

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such property is acquired if it is cooled while lying east and west. It has been proposed to make powerful magnets by placing hot bars of steel to cool between the poles of very powerful electromagnets; and Carré produced strong magnets of iron cast in moulds lying in an intense magnetic field.

107. **Magnetization by Currents of Electricity.** — A current of electricity caused to circulate in a spiral wire wound around a core of iron or steel magnetizes it more powerfully than in any of the preceding operations. In the case of a soft iron core, it is only a magnet while the current continues to flow. Such a combination is termed an **Electromagnet**; it is fully described in Lesson XXXI. Fig. 64 depicts a common form of electromagnet having two coils of insulated copper wire wound upon bobbins that are placed upon the limbs of a soft iron core. The armature is also of soft iron of sufficient thickness. Steel bars may be magnetized by drawing them over the poles of such an electromagnet while the latter is excited by the circulation of the electric current. Elias of Haarlem proposed to magnetize steel bars by passing them through a wire coiled up into a compact ring of many turns, through which a strong current was sent by a voltaic battery.

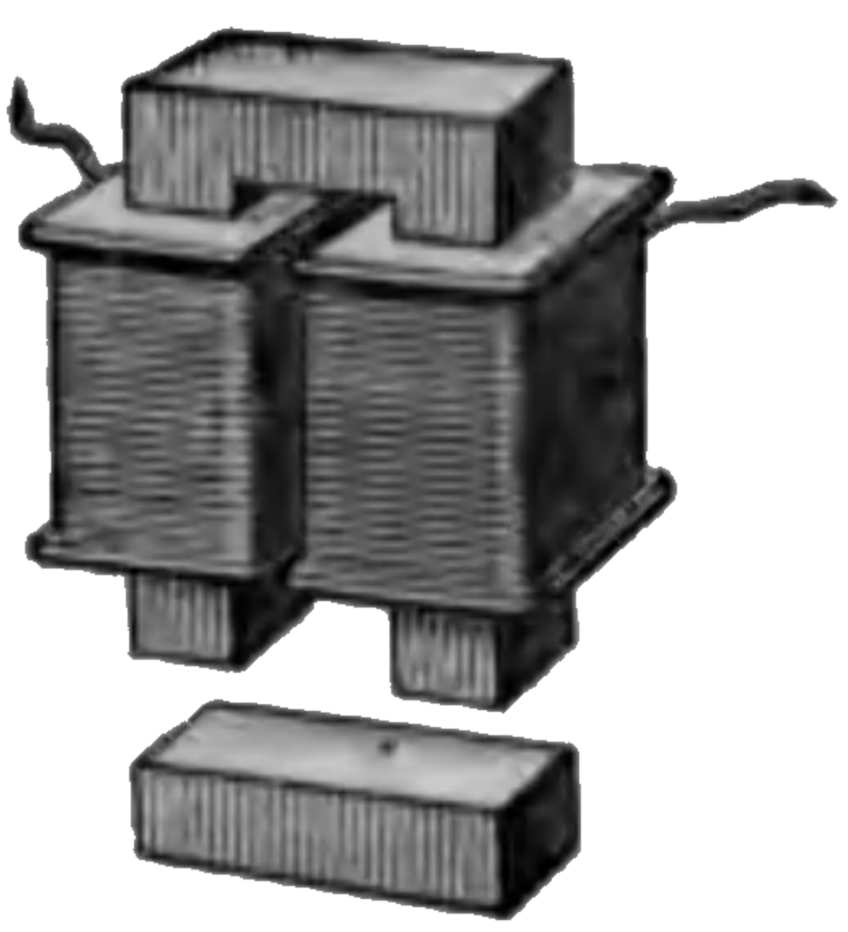


Fig. 64.

108. **Hardening and Tempering of Steel for Magnets.** — There are two ways of hardening steel: (1) by suddenly cooling it from a bright red temperature; (2) by compressing it under hydraulic pressure while it cools slowly. If rods of steel are heated brilliantly red, and then quenched in water, oil, or mercury, they become intensely brittle and *glass-hard*. To temper hard steel it is then gently reheated to near a very dull red heat and softens slightly while acquiring a *straw tint*. If let down still further by continuing the reheating it becomes

a *blue tint*, and is springy and flexible. Short bar magnets retain most magnetism if left glass-hard without tempering. But magnets whose length is more than twenty times their thickness retain more magnetism if tempered down to a straw or even to a blue tint.

109. Destruction of Magnetism. — A steel magnet loses its magnetism partially or wholly if subjected to rough usage, or if purposely hit or knocked about. Newly magnetized magnets lose more strength by rough treatment than those which have been long magnetized. A magnet loses its magnetism, as Gilbert showed, on being raised to a bright red-heat. The slightest vibration will destroy any magnetism remaining in annealed soft iron.

110. Magnets of Unvarying Strength. — Ordinary steel magnets have by no means a permanent or constant magnetism. They soon lose a considerable percentage of their magnetism, and the decay continues slowly for months and years. Every shock or jolt to which they are subjected, every contact with iron, every change of temperature weakens them. Every time that the keeper is slammed on to a horse-shoe magnet it is weakened. For the purpose of making magnetic measurements, and for use as controlling magnets of galvanometers, magnets are, however, required that shall possess the utmost constancy in their strength. Magnets of unvarying strength may be made by attention to following points. Choose a form either of a nearly closed circuit or of a very long rod. Let the steel be hardened as much as possible (see Art. 108 above), then placed in steam at 100° for twenty or thirty hours or more. Then magnetize as fully as possible, and then heat again for five hours in steam. Magnets of a shape constituting a nearly closed circuit are more constant than short straight magnets.

111. Effects of Heat on Magnetization. — If a permanent steel magnet be warmed by placing it in hot or boiling water, its strength will be thereby lessened, though it recovers partially on cooling. Chilling a magnet in-

creases its strength. Cast iron ceases to be attracted by a magnet at a bright red-heat, or at a temperature of about 700° C. Cobalt retains its magnetism at the highest temperatures. Chromium ceases to be magnetic at about 500° C., and nickel at 350° C. Manganese exhibits magnetic attraction only when cooled to – 20° C. It has therefore been surmised that other metals would also become magnetic if cooled to a low enough temperature. Trowbridge found severe cooling to 100° below zero to destroy the magnetism of steel magnets; but Dewar has observed that when cooled to near – 200° C. in liquid oxygen the magnetic properties of iron are nearly twice as high as at 0° C. The magnetic metals at high temperatures do not become diamagnetic, but are still feebly magnetic.

112. Magnetic Saturation.—A magnet to which as powerful a degree of magnetization as it can attain to has been given is said to be *saturated*. A recently magnetized magnet will occasionally appear to be *super-saturated*, possessing even after the application of the magnetizing force has ceased a higher degree of magnetism than it is able to retain permanently. Thus a horse-shoe-shaped steel magnet will support a greater weight immediately after being magnetized than it will do after its armature has been once removed from its poles. Even soft iron after being magnetized retains a small amount of magnetism when its *temporary magnetism* has disappeared. This small remaining magnetic charge is spoken of as *residual magnetism*.

113. Strength of a Magnet.—The "strength" of a magnet is not the same thing as its "lifting power." Its lifting power is a very uncertain quantity depending not only on the shape of its polar surfaces, but on the shape and quality of the mass of iron used as load. Consequently the "strength" of a magnet pole must be measured by the magnetic force which it exerts at a distance on other magnets. Thus, suppose there are two magnets,

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surface, other things being equal. Steel magnets seldom attain a tractive force as great as 40 lbs. per square inch of polar surface. A good steel horse-shoe magnet weighing itself 1 lb. ought to lift 25 lbs. weight. Sir Isaac Newton is *said* to have possessed a little lodestone mounted in a signet ring which would lift a piece of iron 200 times its own weight.

Lesson X.—*Distribution of Magnetism*

115. Magnetic Field. — *The space all round a magnet pervaded by the magnetic forces is termed the "field" of that magnet.* It is most intense near the poles of the magnet, and is weaker and weaker at greater distances away. At every point in a magnetic field the force has a particular strength, and acts in a particular direction. It is possible at any point in a magnetic field to draw a line in the direction of the *resultant magnetic force* acting at that point. The whole field may in this way be mapped out with magnetic lines (Art. 119). For a horse-shoe magnet the field is most intense between the two poles, and the lines of magnetic force are curves which pass from one pole to the other across the field. A practical way of investigating the distribution of the magnetic lines in a field is given in Art. 119, under the title "Magnetic Figures." When the armature is placed upon the poles of a horse-shoe magnet, the force of the magnet on all the external regions is weakened, for the induction now goes on through the iron of the keeper, not through the surrounding space. In fact a *closed system* of magnets —such as that made by placing four bar magnets along the sides of a square, the N pole of one touching the S

method of magnetizing it. In the best steel magnets made at Haarlem by Van Wetteren this coefficient was from 19·5 to 23, the weights being expressed in kilogrammes.

pole of the next — has no external field of force. A *ring* of steel may thus be magnetized so as to have neither external field nor poles; or rather any point in it may be regarded as a N pole and a S pole, so close together that they neutralize one another's forces.

That poles of opposite name do neutralize one another may be shown by the well-known experiment of hanging a small object — a steel ring or a key — to the N pole of a bar magnet. If now the S pole of another bar magnet be made to touch the first the two poles will neutralize each other's actions, and the ring or key will drop down.

116. Breaking a Magnet. — We have already stated that when a magnet is broken into two or more parts, each is a complete magnet, possessing poles, and each is nearly as strongly magnetized as the original magnet.

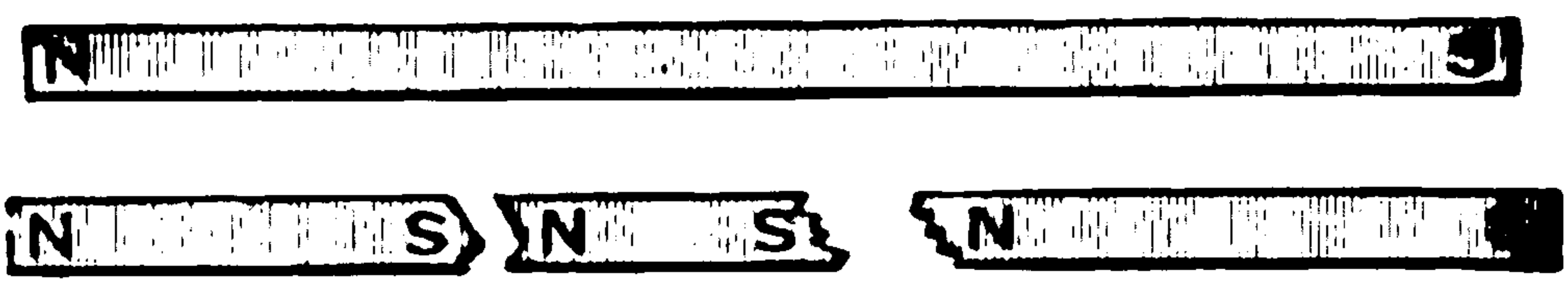


Fig. 65.

Fig. 65 shows this. If the broken parts be closely joined these adjacent poles neutralize one another and disappear, leaving only the poles at the ends as before. If a magnet be ground to powder each fragment will still act as a

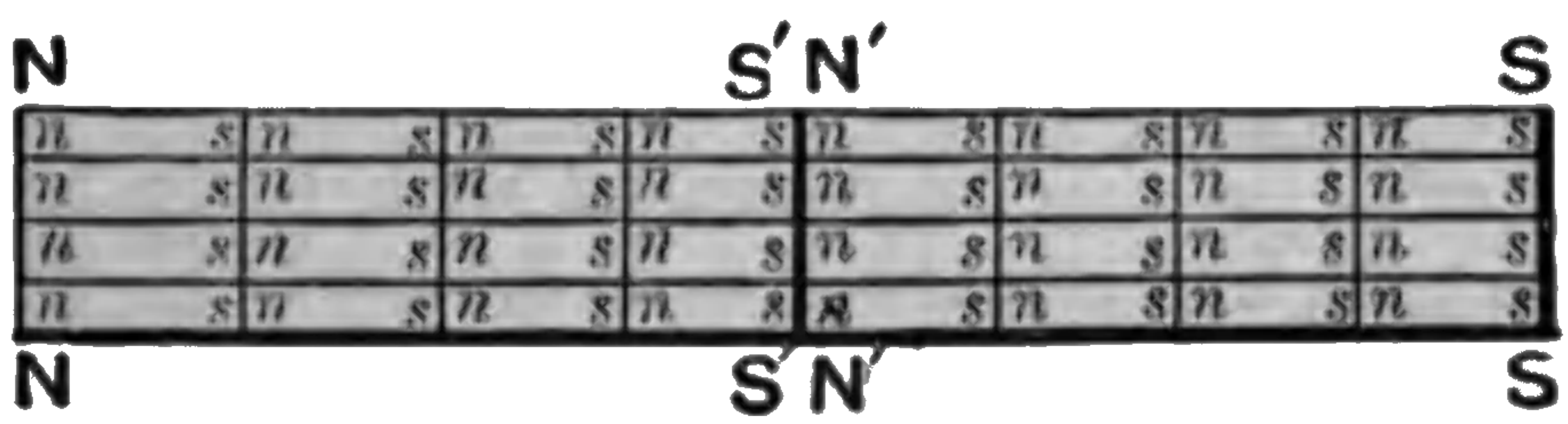


Fig. 66.

little magnet and exhibit polarity. A magnet may therefore be regarded as composed of many little magnets put together, so that their like poles all face one way. Such an arrangement is indicated in Fig. 66, from which it will be seen that if the magnet be broken asunder across

any part, one face of the fracture will present only N poles, the other only S poles. This would be true no matter how small the individual particles.

117. Normal Distribution.—In an ordinary bar magnet the poles are not quite at the ends of the bar, but a little way from it; and it can be shown that this is a result of the way in which the surface magnetism is distributed in the bar. A very long, thin, uniformly magnetized bar has its poles at the ends; but in ordinary thick magnets the "pole" occupies a considerable region, the "free magnetism" falling off gradually from the ends of the bar. In each region, however, a point can be generally determined at which the resultant magnetic forces act, and which may for most purposes be considered as the "pole." In certain cases of irregular magnetization it is possible to have one or more poles between those at the ends. Such poles are called *consequent poles* (see Fig. 70).

118. Lamellar Distribution of Magnetism. Magnetic Shells.—Up to this point the ordinary distribution of magnetism along a bar has been the only distribution considered. It is theoretically possible to have magnetism distributed over a thin sheet so that the whole of one face of the sheet shall have one kind of magnetism, and the other face the other kind of magnetism; such distribution is, however, unstable. If an immense number of little magnets were placed together side by side, like the cells in a honeycomb, all with their N-seeking ends upwards, and S-seeking ends downwards, the whole of one face of the slab would be one large flat N-seeking pole, and the other face S-seeking. Such a distribution as this over a surface or sheet is termed a lamellar distribution, to distinguish it from the ordinary distribution along a line or bar, which is termed, for distinction, the solenoidal, or circuital, distribution. A lamellarly magnetized magnet is sometimes spoken of as a **magnetic shell.**

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intense between the poles, but spreads beyond them in wide curves. Faraday, who made a great use of this method of investigating the distribution of magnetism in various "fields," gave to the lines the name of **lines of force**. They represent, as shown by the action on little magnetic particles which set themselves thus in obedience to the attractions and repulsions in the field, the resultant direction of the forces at every point; for each particle tends to assume the direction of the force jointly due to the simultaneous action of both poles; hence the curves of filings may be taken to represent visibly the invisible *lines of magnetic force.** Faraday pointed out that these "lines of force" map out the magnetic field, showing by their position the direction of the magnetic force, and by their number its intensity. If a small N-seeking pole could be obtained alone, and put down on any one of these lines of force, it would tend to move along that line from N to S; a single S-seeking pole would

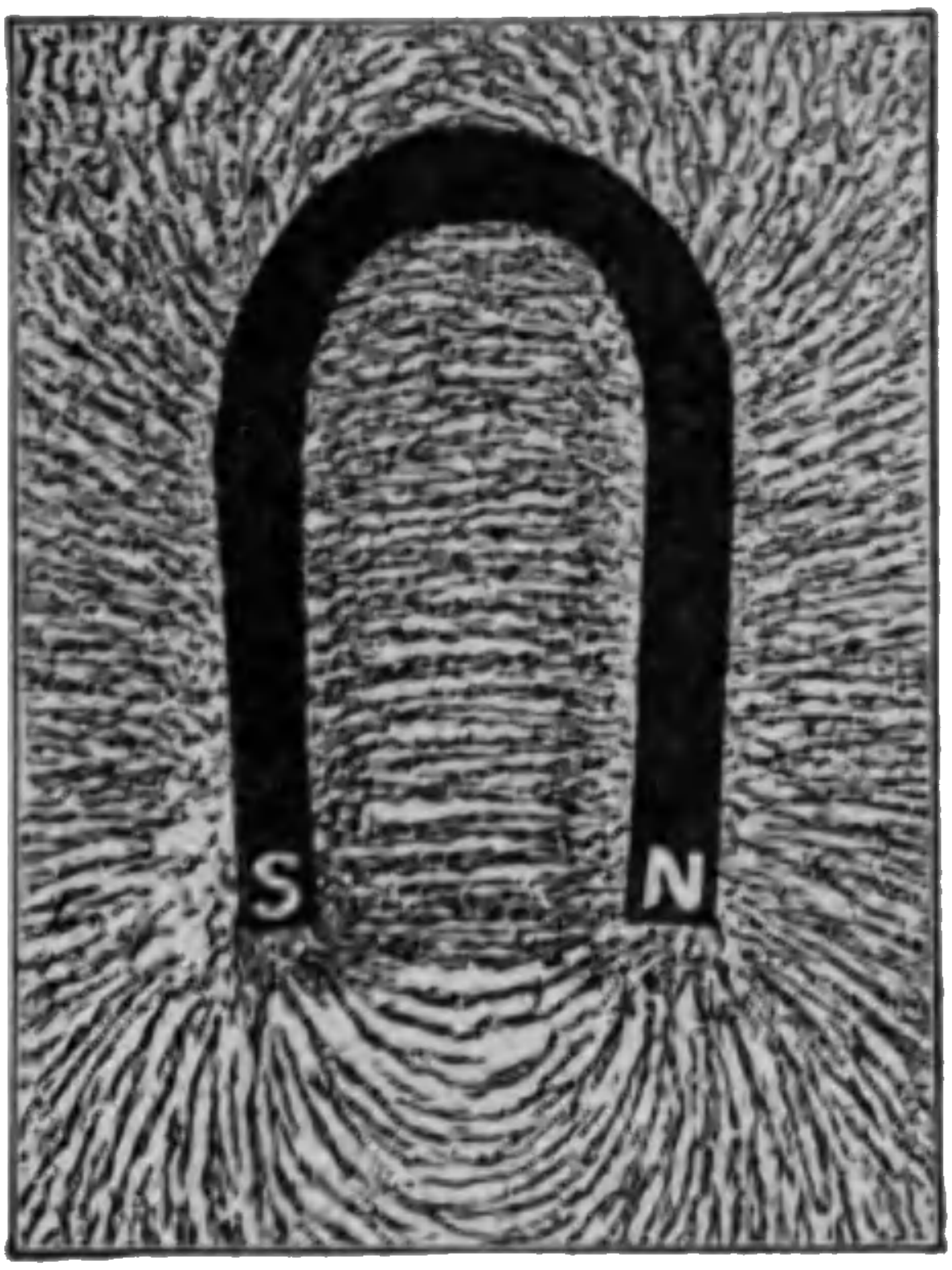


Fig. 68.

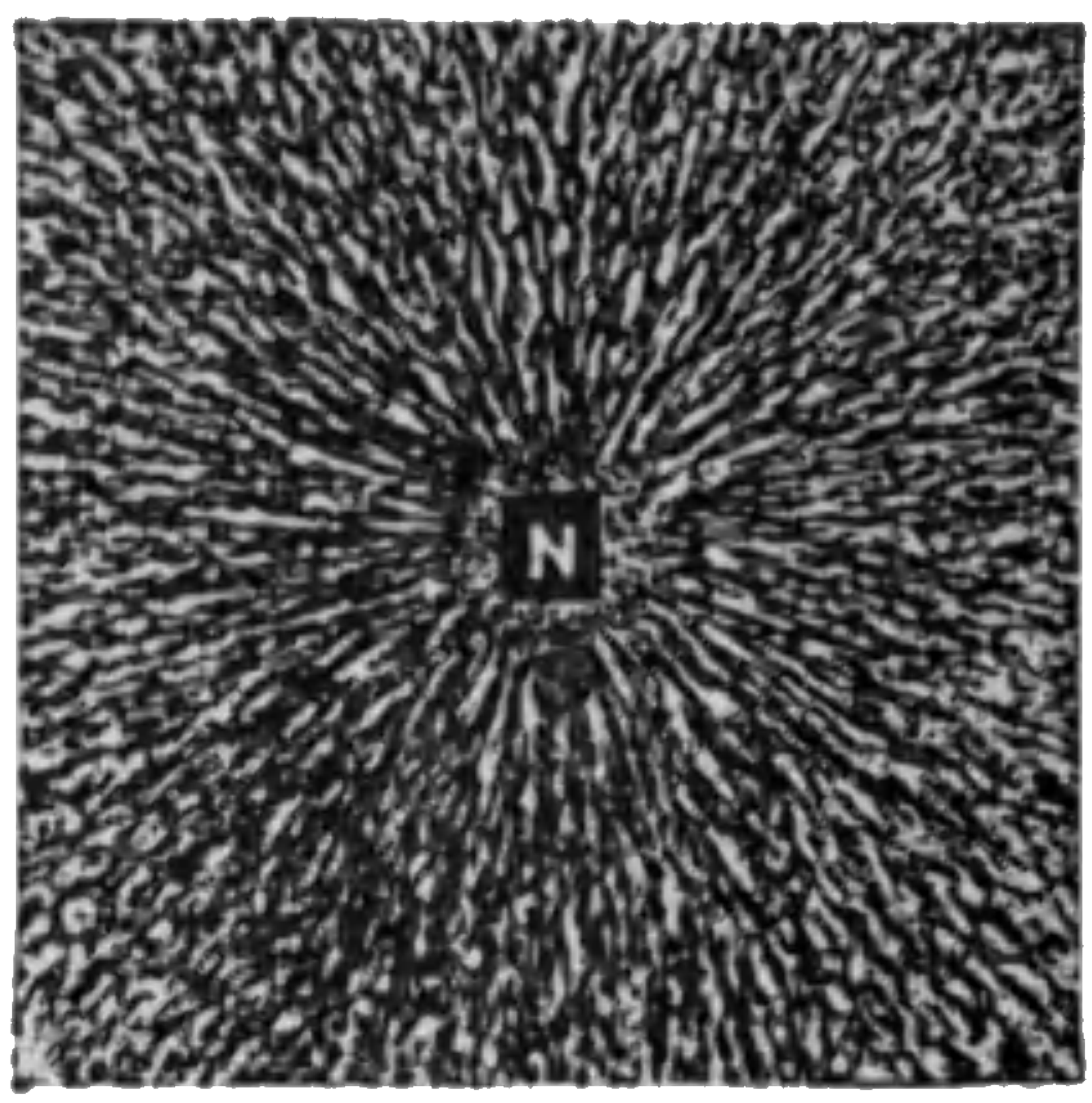


Fig. 69.

* Or rather the component part of the magnetic force resolved into the plane of the figure; which is not quite the same thing, for above the poles the filings stand up nearly vertically to this plane.

tend to move along the line in an opposite direction. In Fig. 69, which is the field about one end of a bar magnet, the magnetic lines are simply radial. Faraday also pointed out that the actions of attraction or repulsion in the field are always related to the directions in the field of the magnetic lines. He assigned to these lines of force certain physical properties (which are, however, only true of them in a secondary sense), viz. that they tend to shorten themselves from end to end, and that they repel one another as they lie side by side. The modern way of stating the matter is, that in every magnetic field there are certain stresses, consisting of a tension along the lines of force, and a pressure across them.

120. **Consequent Poles.** — The method of sprinkling filings may be applied to ascertain the presence of *conse-*

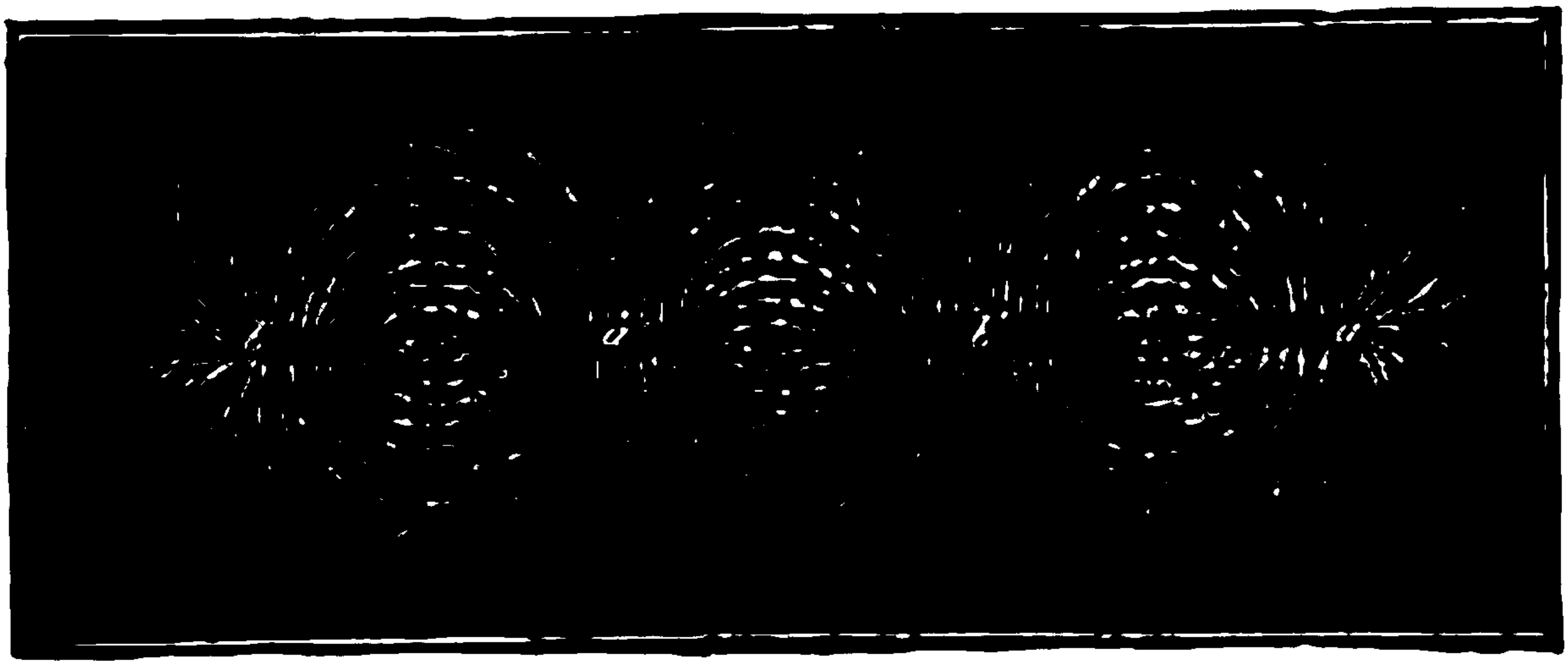


Fig. 70.

quent poles in a bar of steel, the figure obtained resembling that depicted in Fig. 70. Such a state of things is produced when a strip of very hard steel is purposely irregularly magnetized by touching it with strong magnets at certain points. A strip thus magnetized virtually consists of several magnets put end to end, but in reverse directions, NS, SN, etc. Consequent poles can also be produced in an electromagnet by reversing the direction in which the wire is coiled around part of the core.

121. **Fields mapped by Filings.** — The forces pro-

ducing attraction between unlike poles, and repulsion between like poles, are beautifully illustrated by the magnetic figures obtained in the fields between the poles in the two cases, as given in Figs. 71 and 72. In Fig. 71 the poles are of opposite kinds, and the lines of force curve across out of one pole into the other; while in Fig.

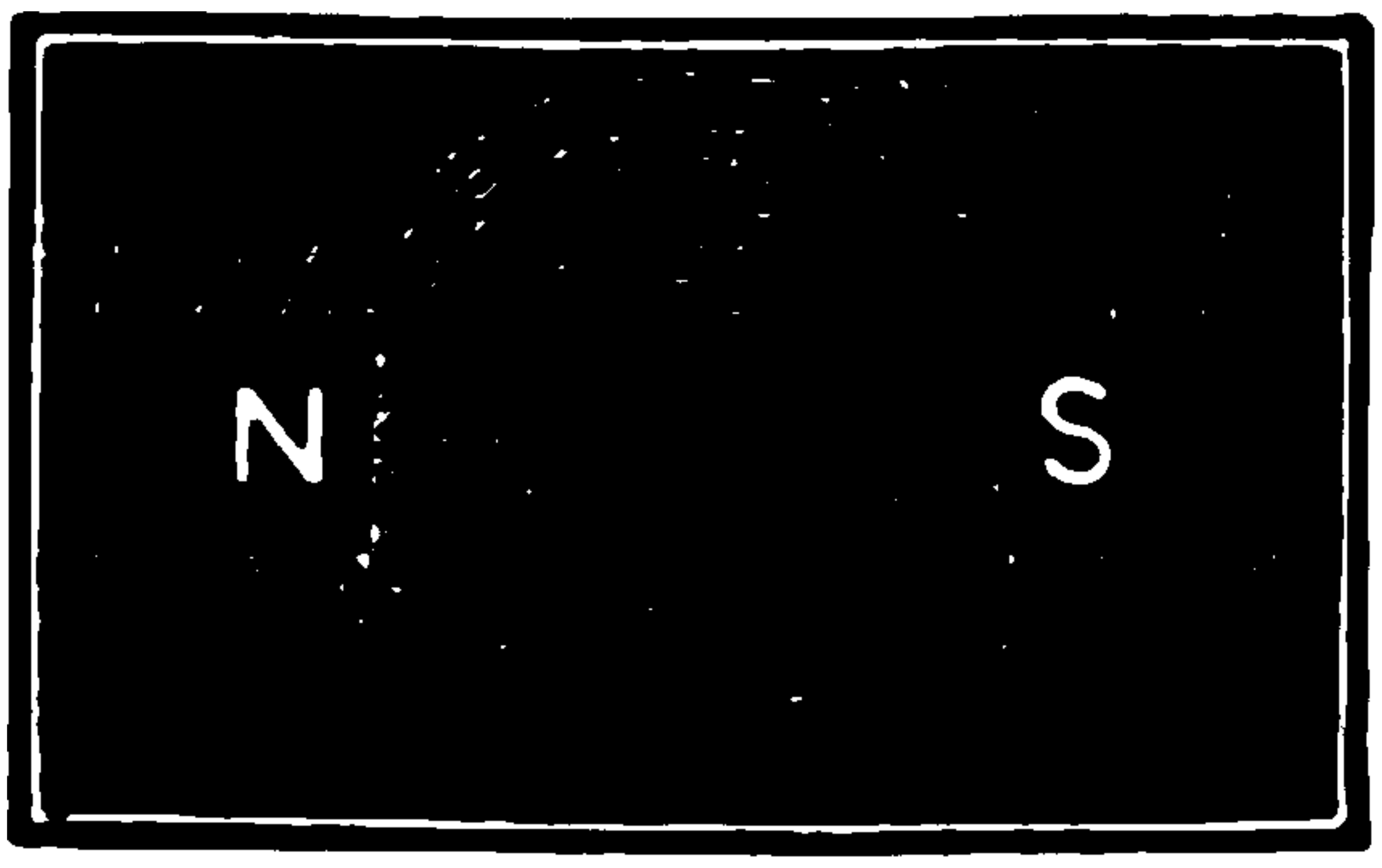


Fig. 71.

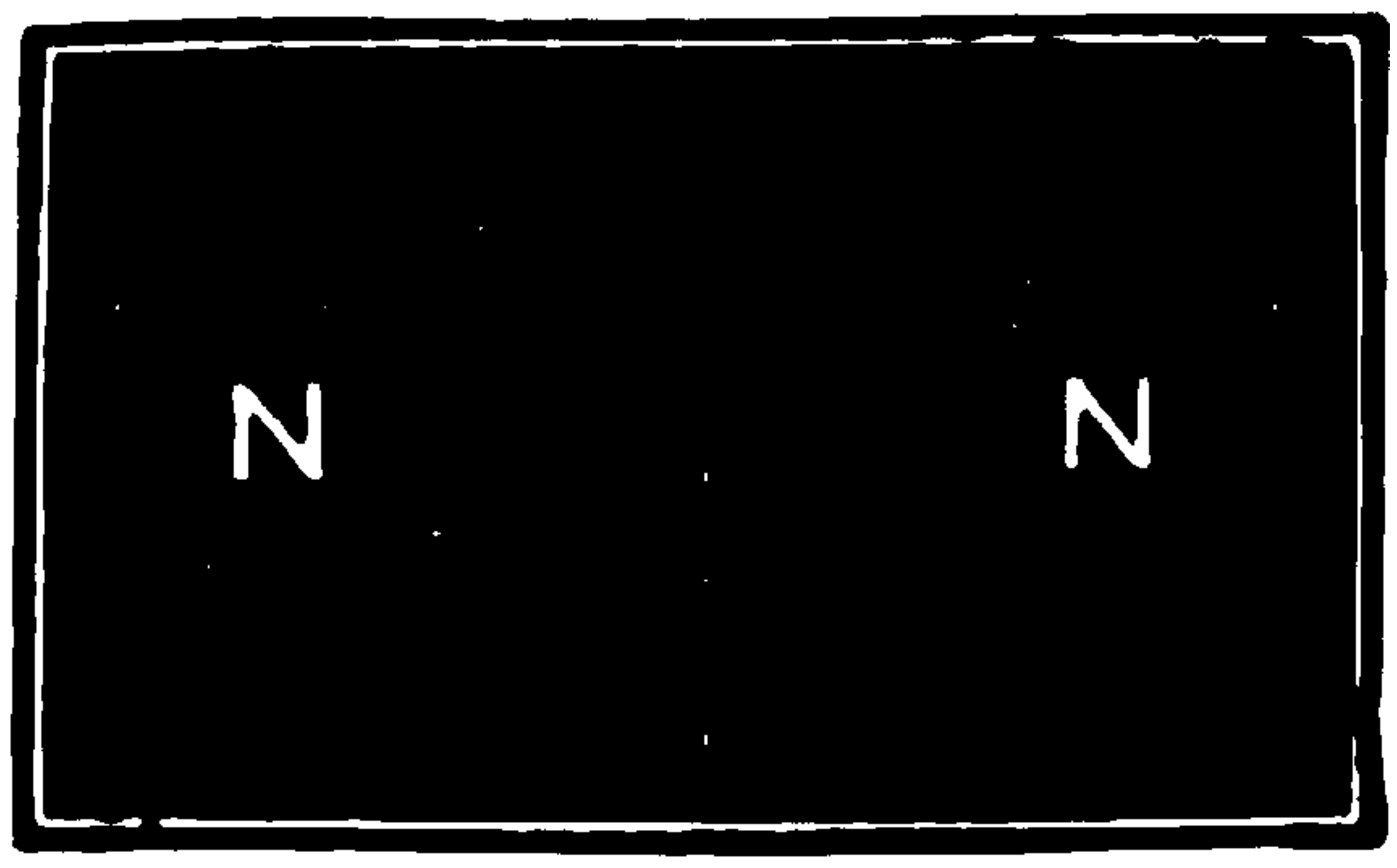


Fig. 72.

72, which represents the action of two similar poles, the lines of force curve away as if repelling one another, and turn aside at right angles.

122. Magnetic Writing. — Another kind of magnetic figures was discovered by De Haldat, who wrote with the pole of a magnet upon a thin steel plate (such as a saw-blade), and then sprinkled filings over it. The writing, which is quite invisible in itself, comes out in the lines of filings that stick to the magnetized parts; this magic writing will continue in a steel plate many months.

123. Surface Magnetization. — In many cases the magnetism imparted to magnets is confined chiefly to the outer layers of steel. If a short bar magnet be put into acid so that the outer layers are dissolved away, it is found that it has lost its magnetism when only a thin film has been thus removed. A short hollow steel tube when magnetized is nearly as strong a magnet as a solid rod of the same size. Long thin magnets, and those that are curved so as nearly to form a closed circuit can be much more thoroughly magnetized. If a bundle of steel plates are magnetized while bound together, it will be

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phenomena point to a theory of magnetism very different from the old notion of fluids. It appears that every particle of a magnet is itself a magnet, and that the magnet only becomes a magnet as a whole by the particles being so turned as to point one way. The act of magnetizing consists in turning the molecules more or less into one particular direction. This conclusion is supported by the observation that if a glass tube full of iron filings is magnetized, the filings can be seen to set themselves endways, and that, when thus once set, they act as a magnet until shaken up. It appears to be harder to turn the individual molecules of solid steel than those of soft iron; but, when once so set, they remain end-on unless violently struck or heated. As Weber, who propounded this notion of molecular magnetism, pointed out, it follows from this theory that when all the particles are turned end-on the limits of possible magnetization would have been attained. Some careful experiments of Beetz on iron deposited by electrolysis entirely confirm this conclusion, and add weight to the theory. Fig. 73 may be taken to represent a non-magnetized piece of iron or steel in which the arrangement of the particles is absolutely miscellaneous: they do not point in any one direction more than another. When magnetized slightly, there will be a greater percentage pointing in the direction of the magnetizing force. When fully magnetized — if that were possible — they would all point in the same direction as in Fig. 74.

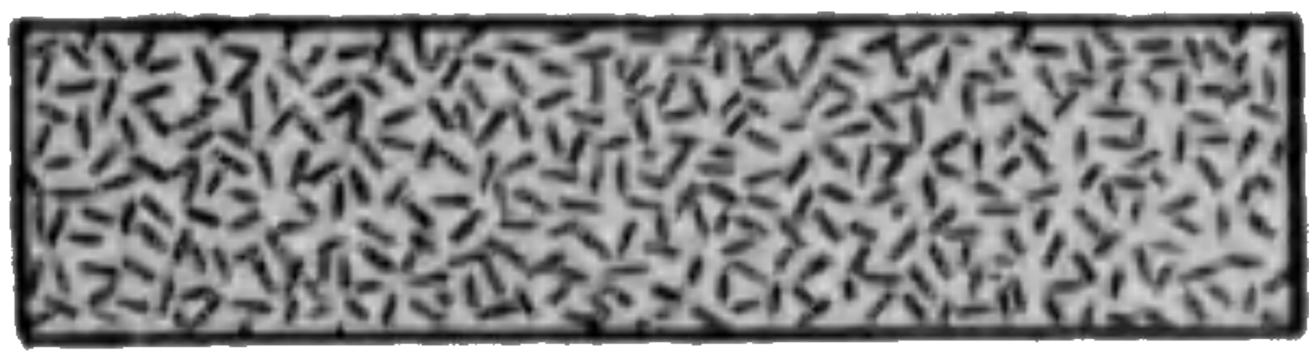


Fig. 73.

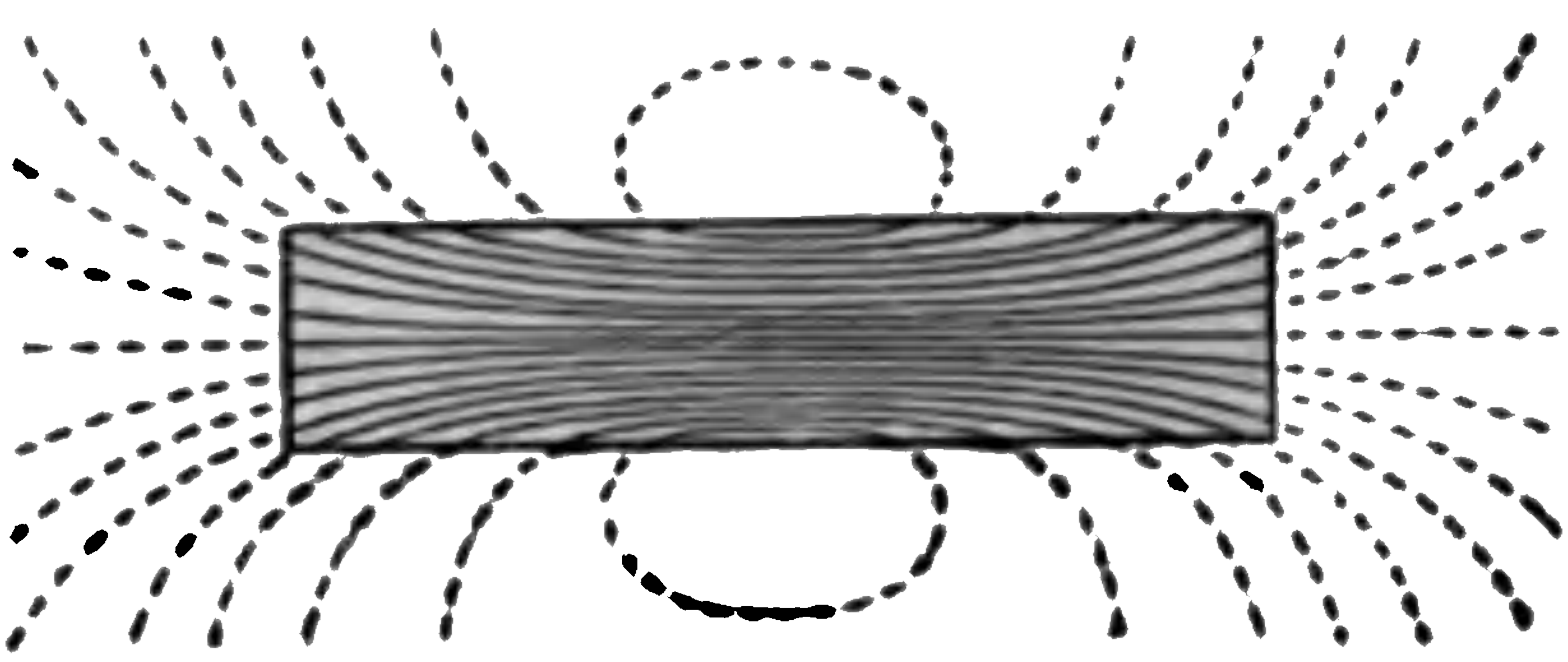


Fig. 74.

In very few cases, however, is the magnetization uniform throughout the whole length of a bar: the particles are more fully completely turned into line at the middle part of the bar than at the ends.

If the intrinsic magnetization of the steel at every part of a magnet were equal, the free poles would be found only at the end surfaces; but the fact that the free magnetism is not at the ends merely, but diminishes from the ends towards the middle, shows that the intensity of the intrinsic magnetization must be less towards and at the ends than it is at the middle of the bar. In Fig. 74 an attempt is made to depict this. It will be noticed that the magnetic lines run through the steel and emerge into the air in curves. Some of the lines do not run all the length of the bar but leak out at the sides. If the bar were uniformly magnetized the lines would emerge at the ends only. It is clear that the middle piece is more thoroughly magnetized than any other part. Magnetism in fact consists of a sort of grain or structure conferred upon the steel. Wherever this structure comes up at a surface, there the surface properties of magnetism are found. A pole is simply a region where the magnetic lines pass through the surface of the steel or iron.

The optical phenomena led Clerk Maxwell to the further conclusion that these longitudinally-set molecules are rotating round their long axes, and that in the "ether" of space there is also a vortical motion along the lines of magnetic induction; this motion, if occurring in a perfect medium (as the "ether" may be considered), producing tensions along the lines of the magnetic field, and pressures at right angles to them, would afford a satisfactory explanation of the magnetic attractions and repulsions which apparently act across empty space.

Hughes, Barus, and others have lately shown that the magnetism of iron and steel is intimately connected with the molecular rigidity of the material. Hughes's researches with the "induction balance" (Art. 514) and

"magnetic balance" (Art. 140) tended to prove that each molecule of a magnetic metal has an absolutely constant inherent magnetic polarity; and that when a piece of iron or steel is apparently neutral, its molecules are internally arranged so as to satisfy each other's polarity, forming closed magnetic circuits amongst themselves.

127. Ewing's Theory of Molecular Magnetism.—Weber supposed that there was in hard steel some sort of friction which prevented the molecules when once magnetized from turning hack into higgledy-piggledy positions. Ewing, however, showed that a complete explanation was afforded by supposing the particles to be subject to mutual forces. In any group not subjected to an external magnetizing force the particles will arrange themselves so as to satisfy one another's polarity. Of the

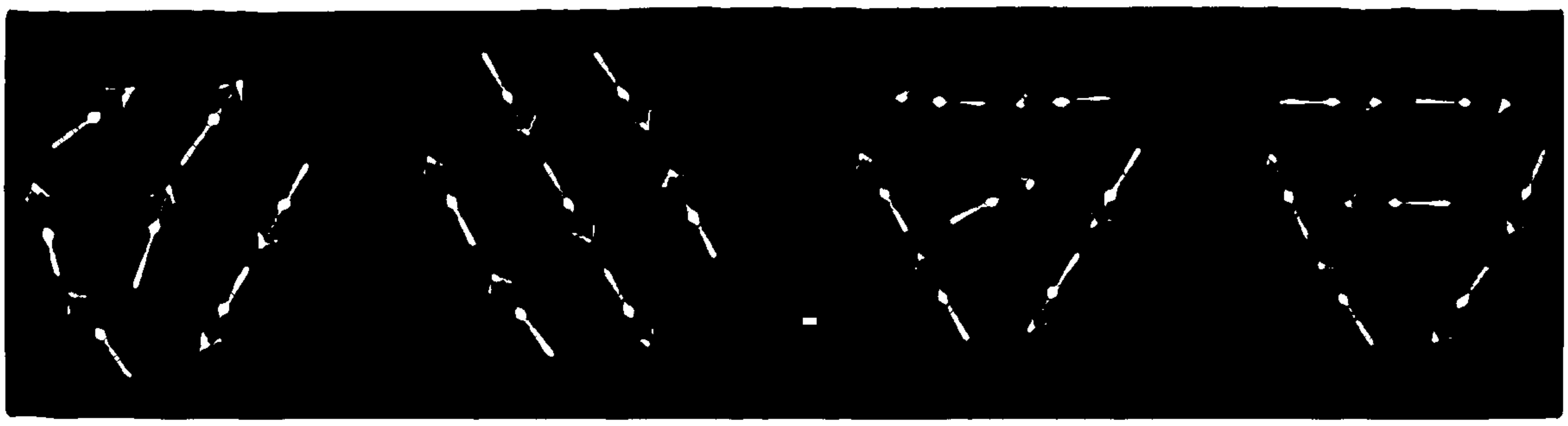


Fig. 75.

possible groupings some are, however, unstable. Four possible stable groupings of six pivoted needles are shown in Fig. 75. Ewing constructed a model consisting of a large number of pivoted magnetic needles arranged in one layer. When these needles were simply agitated and allowed to come to rest they settled down in miscellaneous groups; but when acted upon by a gradually increasing magnetic force they turned round, the operation showing three stages—(i.) with very small magnetizing force the needles merely turned through a small angle; (ii.) when a certain force was applied the groupings became unstable, some of the needles suddenly swinging round to a new position, with the result that the majority of the needles

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A of a magnet be brought near it, the iron is thereby inductively magnetized; it turns round and points towards the magnet pole, setting itself as nearly as possible along a line of force, its near end *b* becoming a S-seeking pole, and its farther end *a* becoming a N-seeking pole. Now the pole *b* will be attracted and the pole *a* will be repelled. But these two forces do not exactly equal one another, since the distances are unequal. The repulsion will (by the law of inverse squares) be proportional to $\frac{1}{(Aa)^2}$; and the attraction will be proportional to $\frac{1}{(Ab)^2}$. Hence the bit of iron *a*, *b* will experience a pair of forces, turning it into a certain direction, and also a total force drawing it bodily toward A. Only those bodies are attracted by magnets in which magnetism can thus be induced; and they are attracted only because of the magnetism induced in them.

We mentioned, Art. 91, that a magnet needle floating freely on a bit of cork on the surface of a liquid, is acted upon by forces that give it a certain direction, but that, unlike the last case, it does not tend to rush as a whole either to the north or to the south. It experiences a rotation, because the attraction and repulsion of the magnetic poles of the earth act in a certain direction; but since the magnetic poles of the earth are at a distance enormously great as compared with the length from one pole of the floating magnet to the other, we may say that, for all practical purposes, the poles of the magnet are at the same distance from the N pole of the earth. The attracting force on the N-pointing pole of the needle is therefore practically no greater than the repelling force acting on the S-pointing pole, hence there is no motion of translation given to the floating needle as a whole: it is *directed*, not *attracted*.

130. Measurement of Magnetic Forces.—The truth of the law of inverse squares can be demonstrated by experiment. But this implies that we have some means

of measuring accurately the amount of the magnetic forces of attraction or repulsion. Magnetic force may be measured in any one of the four following ways: (1) by observing the time of swing of a magnetic needle oscillating under the influence of the force; (2) by observing the deflexion it produces upon a magnetic needle which is already attracted into a different direction by a force of known intensity; (3) by balancing it against the torsion of an elastic thread; (4) by balancing it against the force of gravity as brought into play in attempting to deflect a magnet hung by two parallel strings (called the *bifilar* suspension), for these strings cannot be twisted out of their parallel position without raising the centre of gravity of the magnet.

131. Deflexion Experiment.—Fig. 77 shows an apparatus in which a compass-needle can be deflected by one pole of a magnet made of a long thin bar of steel, so mounted that its upper pole is always over the centre of the needle, and therefore has no tendency to turn it. So set, it acts as a one-pole magnet, the pole of which can be placed at different distances from the compass-needle. It is found, using a proper tangent-scale (see Art. 211) for the compass-needle, that when the distance is doubled the deflecting force is reduced to one quarter, and so forth.

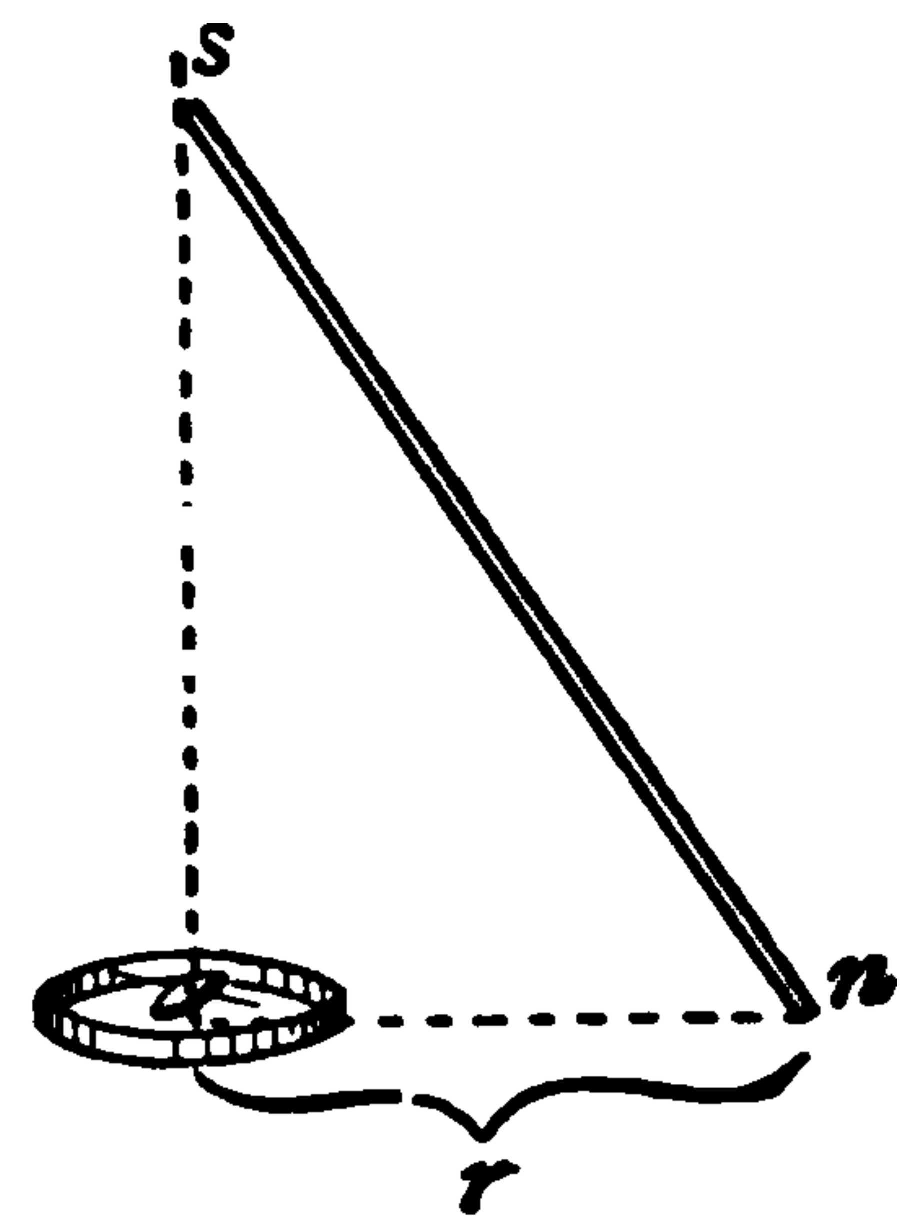


Fig. 77.

132. The Torsion Balance.—Coulomb applied the Torsion Balance to the measurement of magnetic forces. The main principles of this instrument (as used to measure forces of electrostatic repulsion) were described on p. 20. Fig. 78 shows how it is arranged for measuring magnetic repulsions.

To prove the law of inverse squares, Coulomb made the following experiment:—The instrument was first adjusted

so that a magnetic needle, hung in a copper stirrup to the fine silver thread, lay in the magnetic meridian without the wire being twisted. This was done by first putting in the magnet and adjusting roughly, then replacing it by a copper bar of equal weight, and once more adjusting, thus diminishing the error by repeated trials. The next

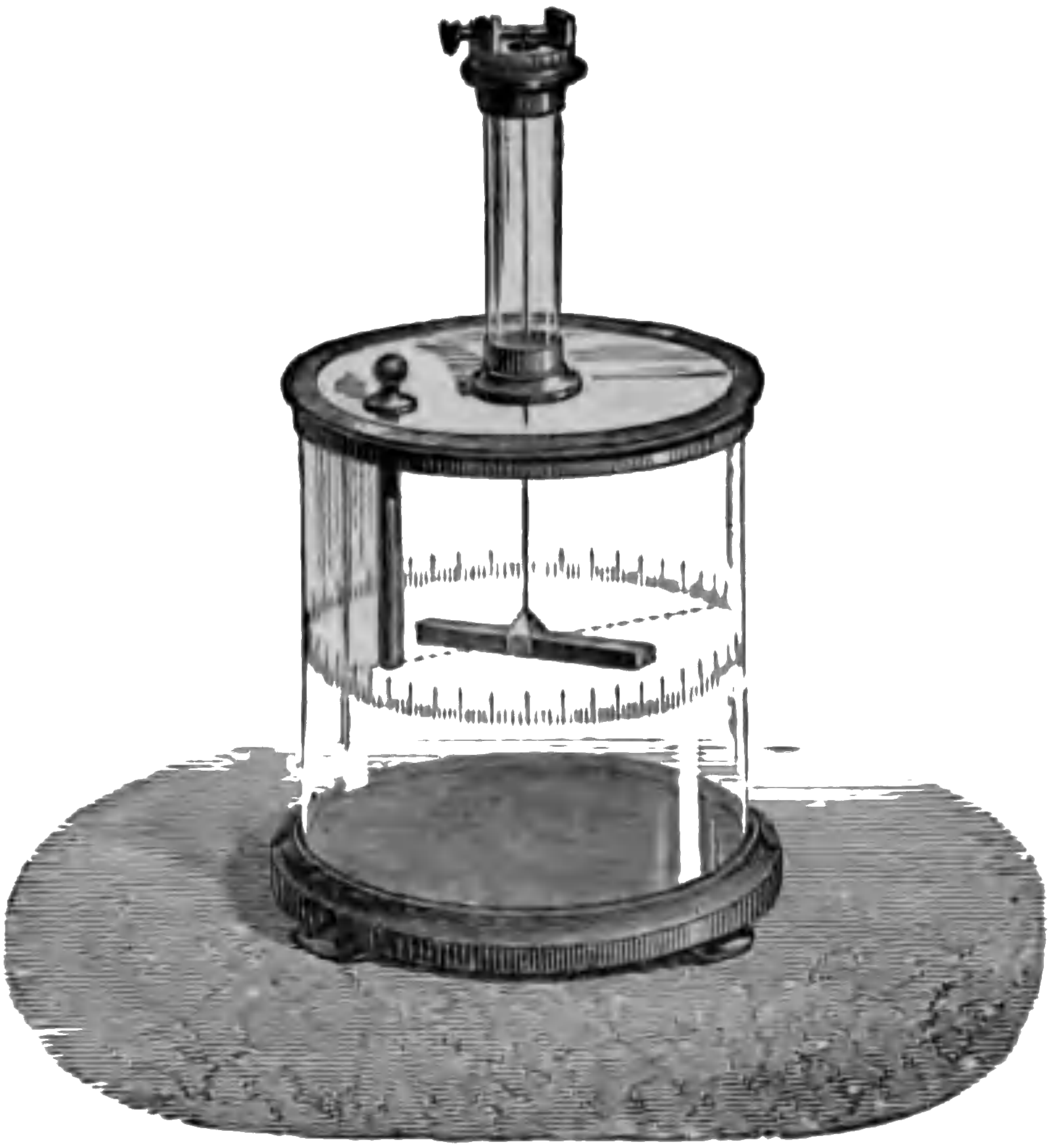


Fig. 78.

step was to ascertain through what number of degrees the torsion-head at the top of the thread must be twisted in order to drag the needle 1° out of the magnetic meridian. In the particular experiment cited it was found that 35° of torsion corresponded to the 1° of deviation of the magnet; then a magnet was introduced through the lid, that pole being downwards which repelled the pole of the

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very nearly equal times. In fact, they follow a law similar to that of the oscillations executed by a pendulum swinging under the influence of gravity. The law of pendular vibrations is, that *the square of the number of oscillations executed in a given time is proportional to the force.* Hence we can measure magnetic forces by counting the oscillations made in a minute by a magnet. It must be remembered, however, that the actual number of oscillations made by any given magnet will depend on the weight of the magnet and on its leverage around its centre, as well as upon the strength of its poles, and on the intensity of the field in which it may be placed (see calculations, Art. 361).

We can use this method to compare the intensity of the force of the earth's magnetism * at any place with that at any other place on the earth's surface, by oscillating a magnet at one place and then taking it to the other place and oscillating it there. If, at the first, it makes a oscillations in one minute, and at the second b oscillations a minute, then the magnetic forces at the two places will be to one another in the ratio of a^2 to b^2.

Again, we may use the method to compare the force exerted at any point by a magnet near it with the force of the earth's magnetism at that point. For, if we swing a small magnetic needle there, and find that it makes m oscillations a minute under the joint action † of the earth's magnetism, and that of the neighbouring magnet, and that, when the magnet is removed, it makes n oscillations a minute under the influence of the earth's magnetism alone, then m^2 will be proportional to the joint forces, n^2 to the force due to the earth's magnetism, and the difference of these, or $m^2 - n^2$ will be proportional to the force due to the neighbouring magnet.

* Or, more strictly, of its *horizontal component.*

† We are here assuming that the magnet is so placed that its force is in a line with that of the earth's magnetism at the point, and that the other pole of the magnet is so far away as not to affect the oscillating needle.

134. Surface Distribution. — We will now apply the method of oscillations to measure the relative quantities of surface magnetism at different points along a bar magnet. The magnet to be examined is set up vertically (Fig. 79). A small magnet, capable of swinging horizontally, is brought near it and set at a short distance away from its extremity, and then oscillated, while the rate of its oscillations is counted. Suppose the needle were such that, when exposed to the earth's magnetism alone, it would perform 3 complete oscillations a minute, and that, when vibrating at its place near the end of the vertical magnet it oscillated 14 times a minute, then the force due to the magnet will be proportional to $14^2 - 3^2 = 196 - 9 = 187$. Nextly, let the oscillating magnet be brought to an equal distance opposite a point a little away from the end of the vertical magnet. If, here, it oscillated 12 times a minute, we know that the force will be proportional to $12^2 - 3^2 = 144 - 9 = 135$. So we shall find that as the force falls off the oscillations will be fewer, until, when we put the oscillating magnet opposite the middle of the vertical magnet, we shall find that the number of oscillations is 3 per minute, or that the earth's force is the only force affecting the oscillations. In Fig. 80 we have indicated the number of oscillations at successive points, as 14, 12, 10, 8, 6, 5, 4, and 3. If we square these numbers and subtract 9 from each, we shall get for the forces at the various points the following: — 187, 135, 91, 55, 27, 16, 7, and 0. These forces may be taken to represent the strength of the free magnetism at the various points, and it is convenient to plot them out graphically in the manner shown in Fig. 80, where the heights of the dotted lines are chosen to a scale to represent proportionally the forces. The curve which

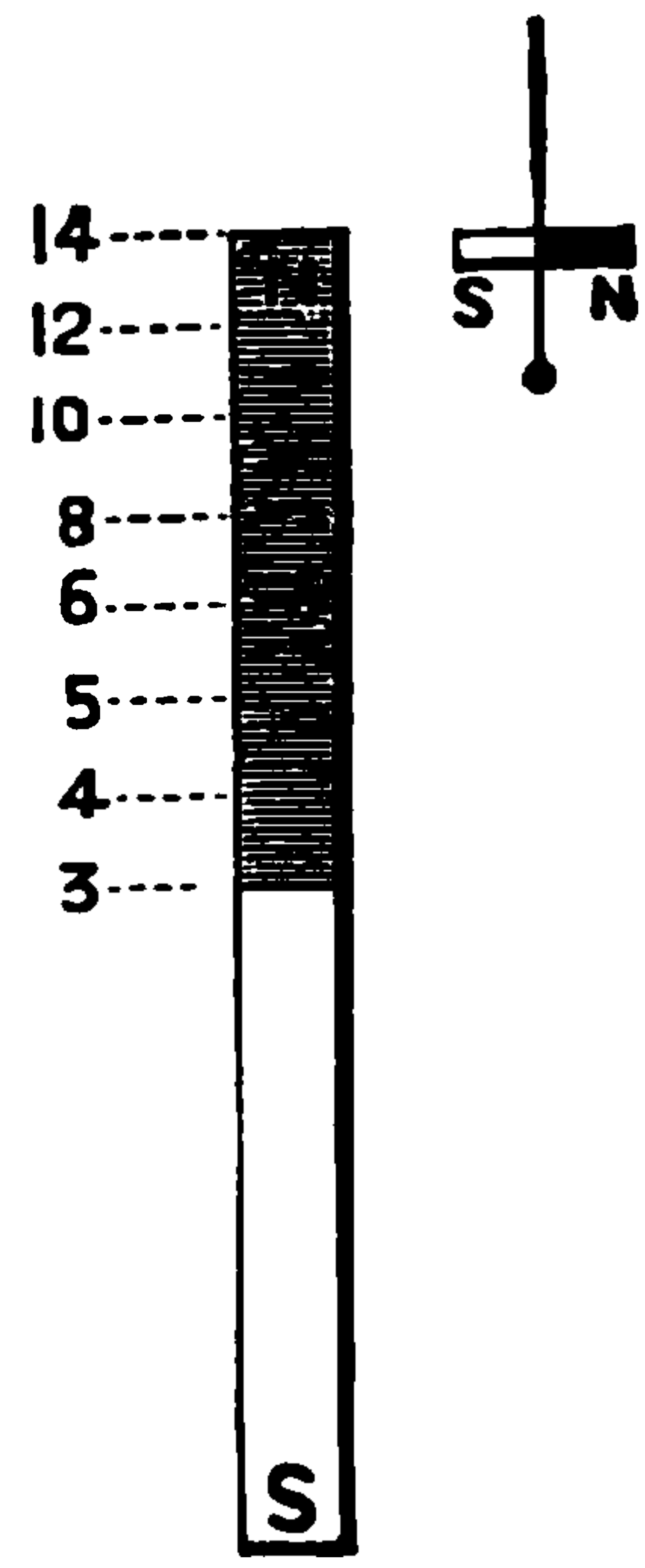


Fig. 79.

joins the tops of these ordinates shows graphically how the force, which is greatest at the end, falls off toward the middle. On a distant magnet pole these forces, thus represented by this curvilinear triangle, would act as if

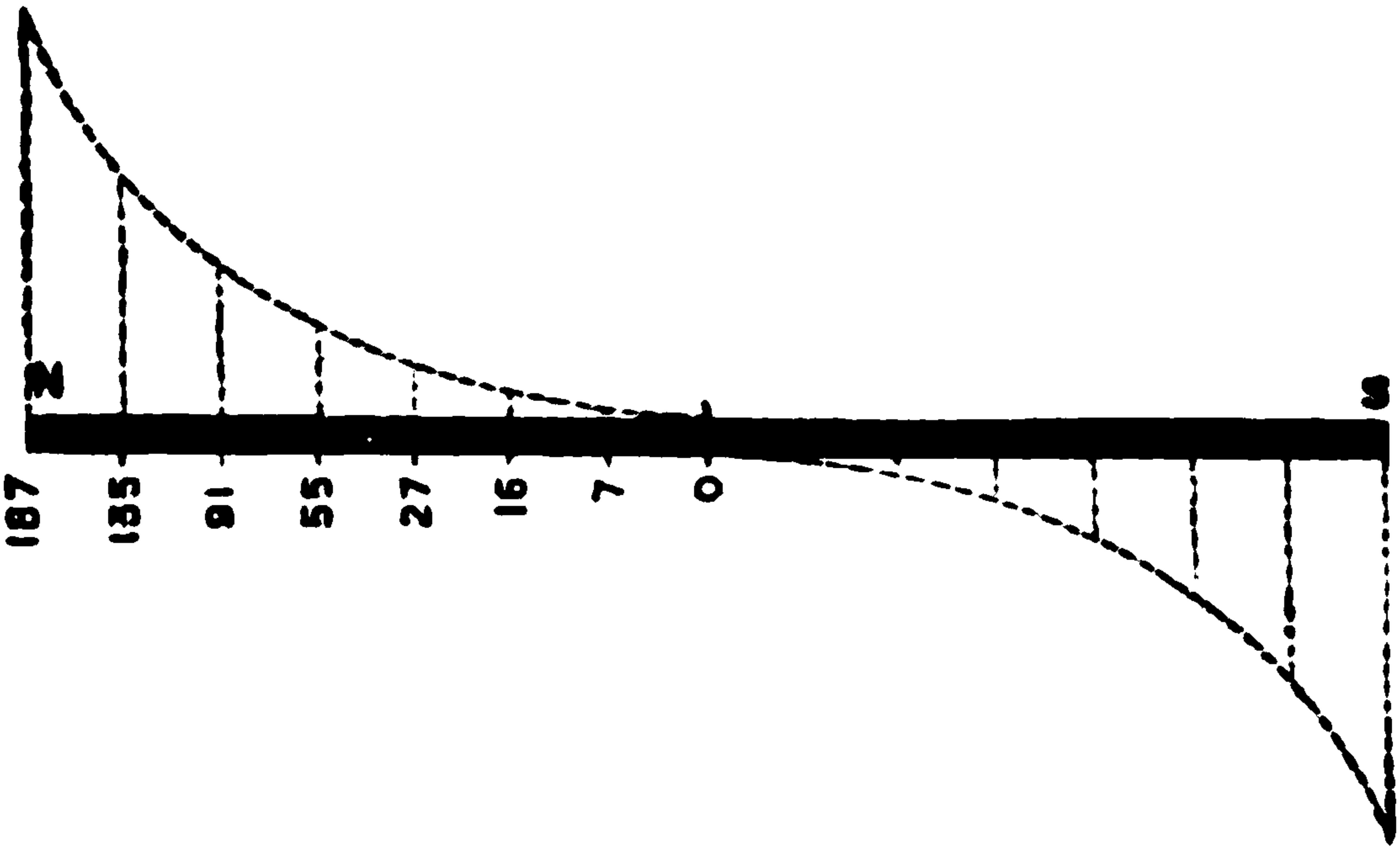


Fig. 90.

concentrated at a point in the magnet opposite the "centre of gravity" of this triangle; or, in other words, the "pole," which is the centre of the resultant forces, is not at the end of the magnet. In thin bars of magnetized steel it is at about $\frac{1}{12}$ of the magnet's length from the end.

135. Magnetic Moment. — It is found that the tendency of a magnet to turn or to be turned by another magnet depends not only on the *strength* m of its poles, but the *length* l between them. The product of these two quantities $m \times l$ is called the **magnetic moment** of the magnet, and is sometimes denoted by the symbol M. As the exact position of a magnet's poles is often unknown, it is easier to determine M than to measure either m or l separately.

136. Method of Deflexions. — There are a number of ways in which the deflexion of a magnet by another magnet may be made use of to measure magnetic forces.*

* The student desirous of mastering these methods of measuring magnetic forces should consult Professor Andrew Gray's *Absolute Measurements in Electricity and Magnetism.*

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obliquely in the field, while the magnetic force acting on A is in the direction of the line PA, and that on B in the direction QB, as shown by the arrows. PQ is the perpendicular distance between these forces; hence the "moment" of the couple, or torque, will be got by multiplying the length PQ by the force exerted on one of the poles. Using the symbol Y for the torque, we may write

$$Y = PQ \times m \cdot H.$$

But PQ is equal to the length of the magnet multiplied by the sine* of the angle AOR, which is the angle of deflexion, and which we will call δ. Hence, using l for the length between the poles of the magnet, we may write the expression for the moment of the couple.

$$Y = mlH \cdot \sin \delta.$$

In words this is: the torque acting on the needle is proportional to its "magnetic moment" ($m \times l$), to the horizontal force of the earth's magnetism, and to the sine of the angle of deflexion.

The reader will not have failed to notice that if the needle were turned more obliquely, the distance PQ would be longer, and would be greatest if the needle were turned round east-and-west, or in the direction EW. Also the torque tending to rotate the magnet will be less and less as the needle is turned more nearly into the direction NS.

137. Law of Tangents.—Now, let us suppose that the deflexion δ were produced by a magnetic force applied at right angles to the magnetic meridian, and tending to draw the pole A in the direction RA. The length of the line RT multiplied by the new force will be the leverage of the new couple tending to twist the magnet into the direction

* If any reader is unacquainted with trigonometrical terms he should consult the note at the end of this lesson, on "Ways of Reckoning Angles."

EW. Now, if the needle has come to rest in equilibrium between these two forces, it is clear that the two opposing twists are just equal and opposite in power, or that the torque due to one couple is equal to that of the other couple. Hence the force in the direction WE will be to the force in the direction SN in the same ratio as PQ is to RT, or as PO is to RO.

Or, calling this force f,

$$f : H = PO : RO.$$

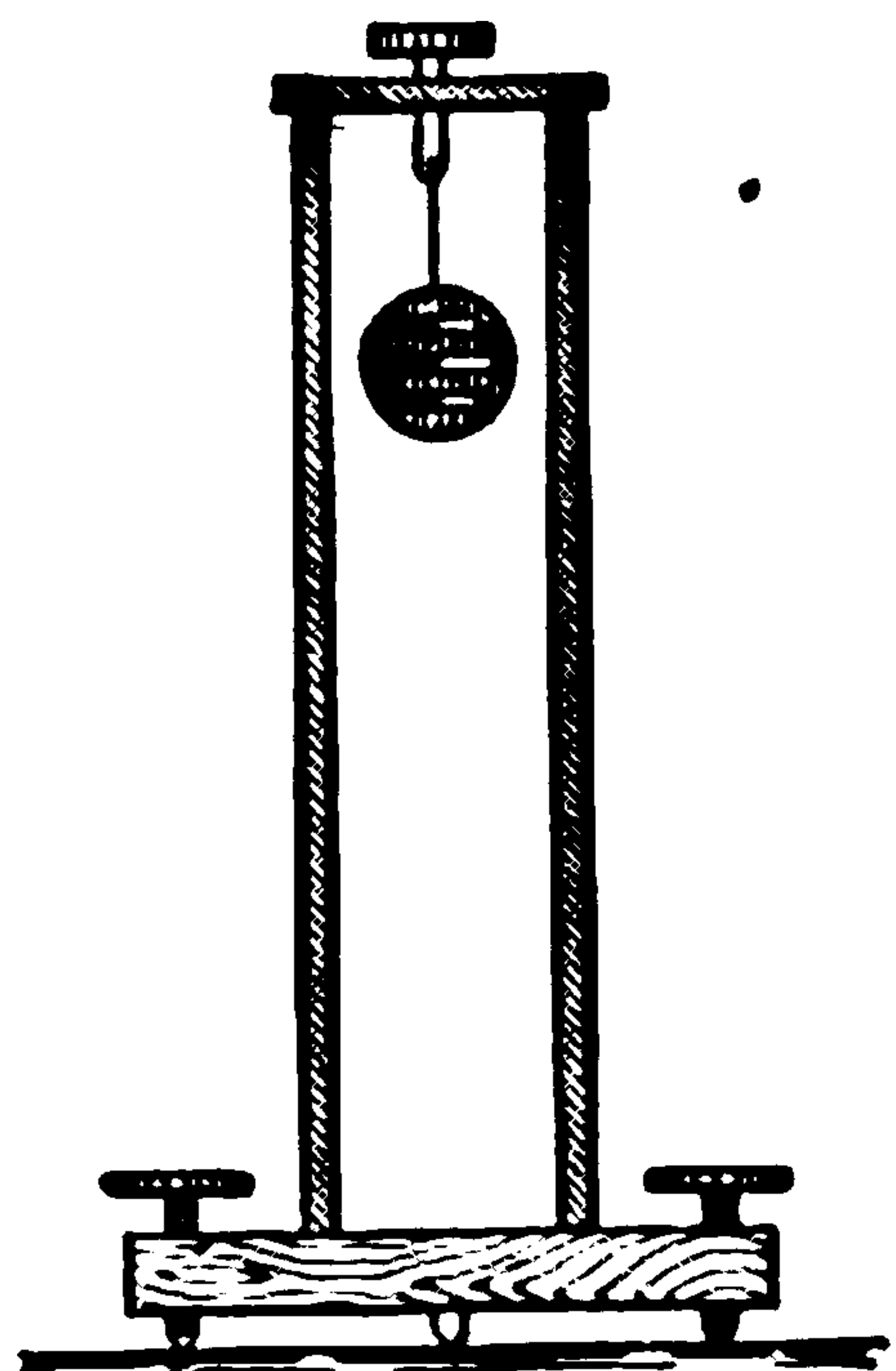
Or $$f = H \frac{PO}{RO}.$$

But $PO = AR$ and $\frac{AR}{RO} = \tan \delta$, hence

$$f = H \tan \delta;$$

or, in other words, *the magnetic force which, acting at right angles to the meridian, produces on a magnetic needle the deflexion* δ, *is equal to the horizontal force of the earth's magnetism at that point, multiplied by the tangent of the angle of deflexion.* Hence, also, two different magnetic forces acting at right angles to the meridian would severally deflect the needle through *angles whose tangents are proportional to the forces.*

This very important theorem is applied in the construction of certain galvanometers (see Art. 212).


Fig. 82.

138. **Magnetometers.**—The name **Magnetometer** is given to any magnet specially arranged as an instrument for the purpose of measuring magnetic forces. The methods of observing the *absolute* values of magnetic forces in *dyne-units* (units in the "C.G.S." system) will be explained in Art. 361

at the end of Lesson XXVII. Very simple magnetometers, consisting of small needles pivoted, or suspended by a fibre, are commonly used for measuring the *relative* values of magnetic forces. One very sensitive form (Fig. 82), to be used, like the reflecting galvanometer (Art. 215), with a beam of light as a pointer, consists of a small thin silvered glass mirror, a half-inch or less in diameter, having two or three very light magnets cemented at its back, suspended by a single thread of cocoon silk, and enclosed in a suitable case. Another useful form (Fig. 83) consists of a short compass-needle poised on a pivot having a light index of aluminium long enough to move over a scale divided into tangent values (see Art. 212).

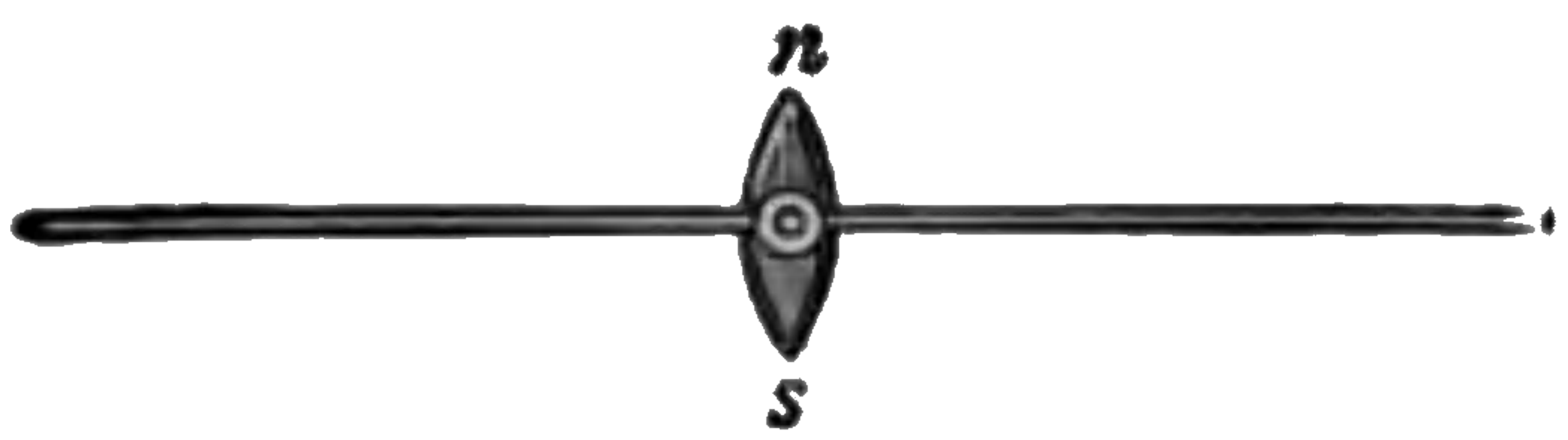


Fig. 83.

A convenient deflexion magnetometer for comparing the magnetic moments (Art. 135) of two magnets is

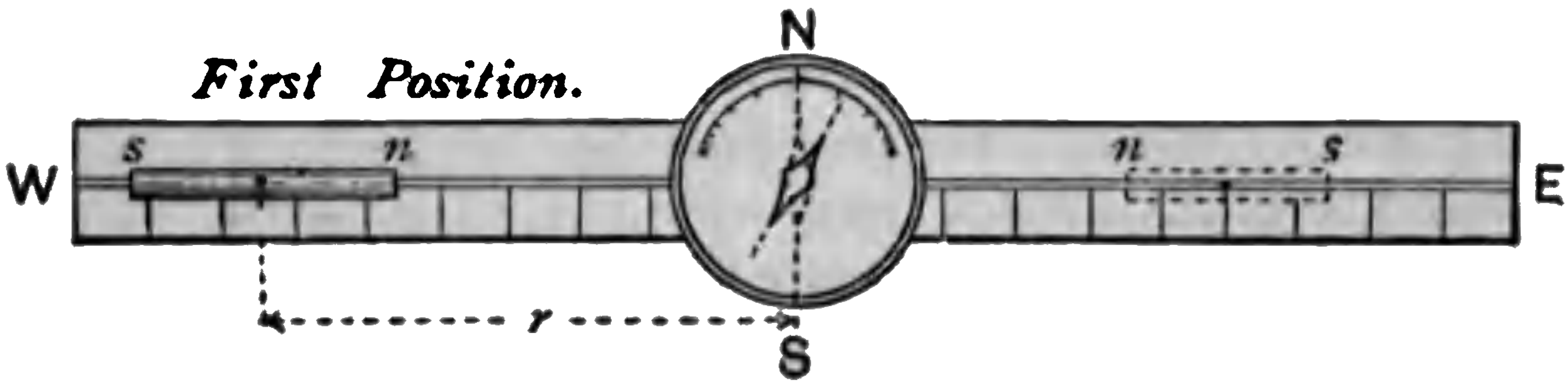


Fig. 84.

afforded by such a tangent compass placed in the middle of a graduated platform (Fig. 84). There are two methods of using this apparatus.

First Position: End-on Method.—The platform being set magnetically east and west, the deflecting magnet is set *end-on*. Under these circumstances the force is found to vary directly as the magnetic moment (Art. 135), and *inversely as the cube* of the distance between the centres of the magnets, or in symbols:—

$$f = 2M/r^3.$$

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is placed in a magnetizing coil A (Fig. 86), and a current is sent round it. It deflects a lightly-suspended indicating needle B, which is then brought to zero by turning a large compensating magnet M upon its centre. A small coil C is added to balance the direct deflecting effect due

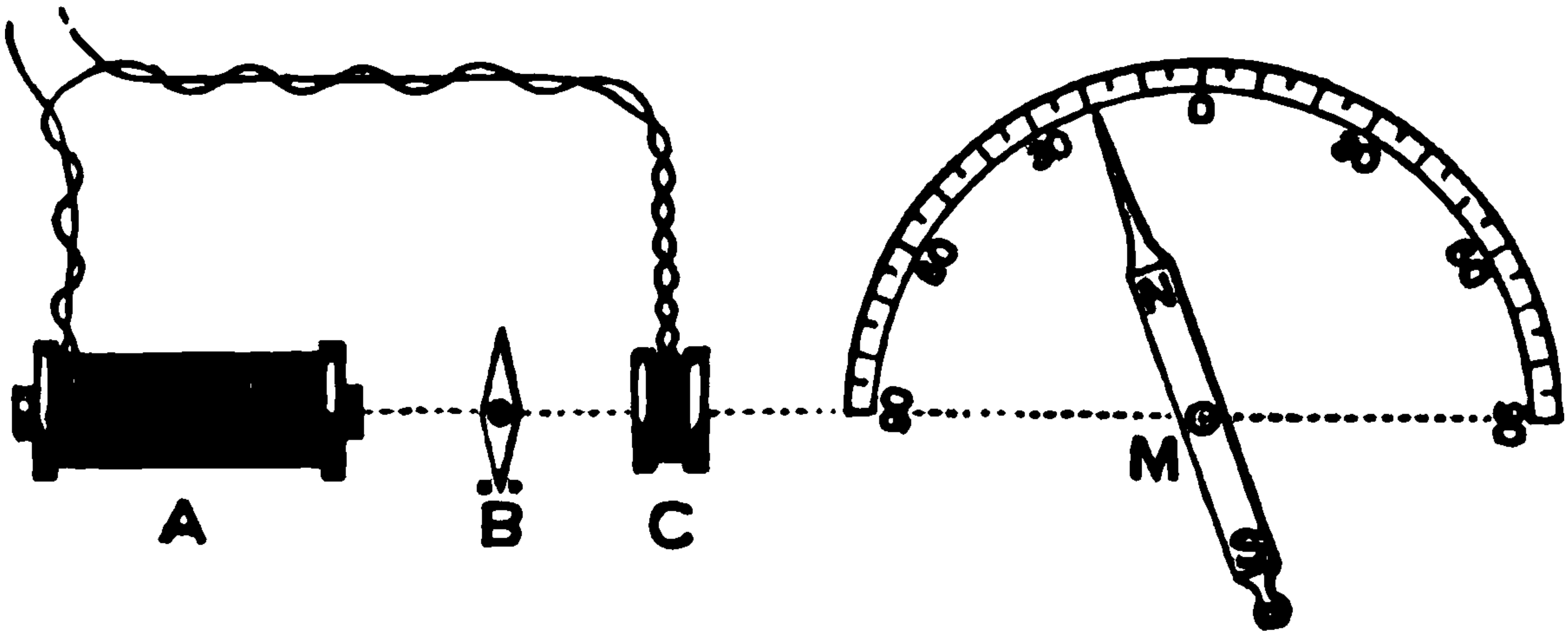


Fig. 86.

to coil A. The author of this book has shown that if the distance from M to B is 2·3 times the length of M, the angle through which M is turned is proportional to the magnetic force due to the iron core at A, provided the angle is less than 60°.

141. Unit Strength of Pole.—The Second Law of Magnetic Force (see Art. 128) stated that the force exerted between two poles was proportional to the product of their strengths, and was inversely proportional to the square of the distance between them. It is possible to choose such a strength of pole that this proportionality shall become numerically an equality. In order that this may be so, we must adopt the following as our unit of strength of a pole, or unit magnetic pole: *A Unit Magnetic Pole is one of such a strength that, when placed at a distance of one centimetre from a similar pole of equal strength it repels it with a force of one dyne* (see Art. 352). If we adopt this definition we may express the second law of magnetic force in the following equation:—

$$f = \frac{m \times m'}{d^2},$$

where f is the force (in dynes), m and m' the strengths of the two poles, and d the distance between them (in centimetres). From this definition is derived the arbitrary convention about magnetic lines. If at any place in a magnetic field we imagine a unit magnetic pole to be set it will be acted upon, tending to move along the lines of the field. Then if at that place we find the force on the pole to be H dynes, we may conceive that there are H lines drawn per square centimetre. For example, if we describe the field as having 50 lines side by side per square centimetre, we mean that a unit pole placed there will be acted on with a force of 50 dynes. This subject is resumed in Lesson **XXVI.**, Art. 338, on the Theory of Magnetic Potential.

142. Theory of Magnetic Curves.—We saw (Art. 119) that magnetic figures are produced by iron filings setting themselves in certain directions in the field of force around a magnet. We can now apply the law of inverse squares to aid us in determining the direction in which a filing will set itself at any point in the field. Let NS (Fig. 87) be a long thin magnet, and P any point in the field due to its magnetism. If the N-seeking pole of a small magnet be put at P, it will be attracted by S and repelled by N; the directions of these two forces will be along the lines PS and PN. The amounts of the forces may be represented by certain lengths marked out along these lines. Suppose the distance PN is twice as great as PS, the repelling force along PN will be $\frac{1}{4}$ as strong as the attracting force along PS. So measure a distance out, PA towards S four times as long as the length PB measured along PN away from N. Find the resultant force in the usual way of compounding mechanical forces, by completing the parallelogram PARB; the diagonal PR represents by its length and direction the magnitude and the direction of the resultant magnetic force at the point P. In fact the line PR represents the line along which a small magnet or an

iron filing would set itself. In a similar way we might ascertain the direction of the lines of force at any point of the field. The little arrows in Fig. 87 show how the lines of force start out from the N pole and curve round to meet in the S pole. The student should compare this

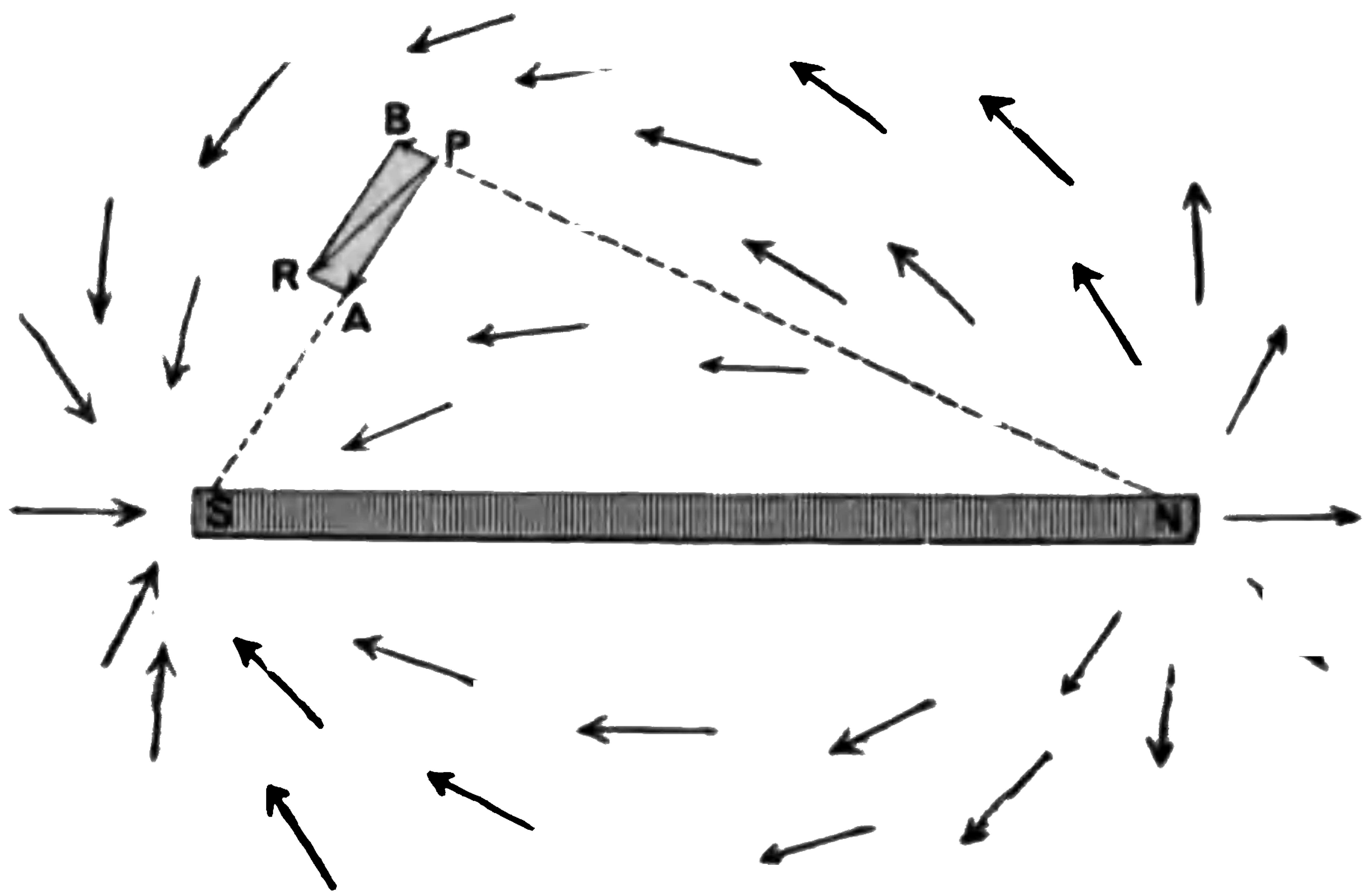


Fig. 87.

figure with the lines of filings of Fig. 67. Henceforth we must think of every magnet as being permeated by these magnetic lines which extend out into the surrounding space. The whole number of magnetic lines which run through a magnet is termed its *magnetic flux* (Art. 337).

143. A Magnetic Paradox.—If the N-seeking pole of a strong magnet be held at some distance from the N-seeking pole of a weak magnet, it will repel it; but if it is pushed up quite close it will be found now to *attract* it. This paradoxical experiment is explained by the fact that the magnetism induced in the weak magnet by the powerful one will be of the opposite kind, and will be attracted; and, when the powerful magnet is near, this induced magnetism may overpower and mask the original magnetism of the weak magnet. The

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that, for convenience, we always use for it the Greek letter π. Hence the length of the circumference of our circle, whose radius is one centimetre, will be 6·28318 . . . centimetres, or 2π centimetres. We can then reckon any angle by naming the length of arc that subtends it on a circle one centimetre in radius. If we choose the angle PCO, such that the curved arc OP shall be just one centimetre long, this will be the angle *one*, or unit of angular measure, or, as it is sometimes called, the angle PCO will be *one* "*radian*." In degree-measure one radian $= \frac{360^\circ}{2\pi} = 57^\circ 17'$ nearly. All the way round the circle will be 2π radians. A right angle will be $\frac{\pi}{2}$ radians.

146. Reckoning by Sines or Cosines. — In trigonometry other ways of reckoning angles are used, in which, however, the angles themselves are not reckoned, but certain "functions" of them called "sines," "cosines," "tangents," etc. For readers not accustomed to these we will briefly explain the geometrical nature of these "functions." Suppose we draw (Fig. 89) our circle as before round centre C, and then drop down a plumb-line PM, on to the line CO; we will, instead of reckoning the angle by the curved arc, reckon it by the length of the line PM. It is clear that if the angle is small, PM will be short; but as the angle opens out towards a right angle, PM will get longer and longer (Fig. 90). The ratio between the length of this line and the radius of the circle is called the "*sine*" *of the angle*, and if the radius is 1 the length of PM will be the value of the sine. It can never be greater than 1, though it may have all values between 1 and −1. The length of the line CM will also depend upon the amount of the angle. If the angle is small CM will be nearly as long as CO; if the angle open out to nearly a right angle CM will be very short. The length of CM (when the radius is 1) is called *the* "*cosine*" *of the angle*. If the angle be called θ, then we may for shortness write these functions:

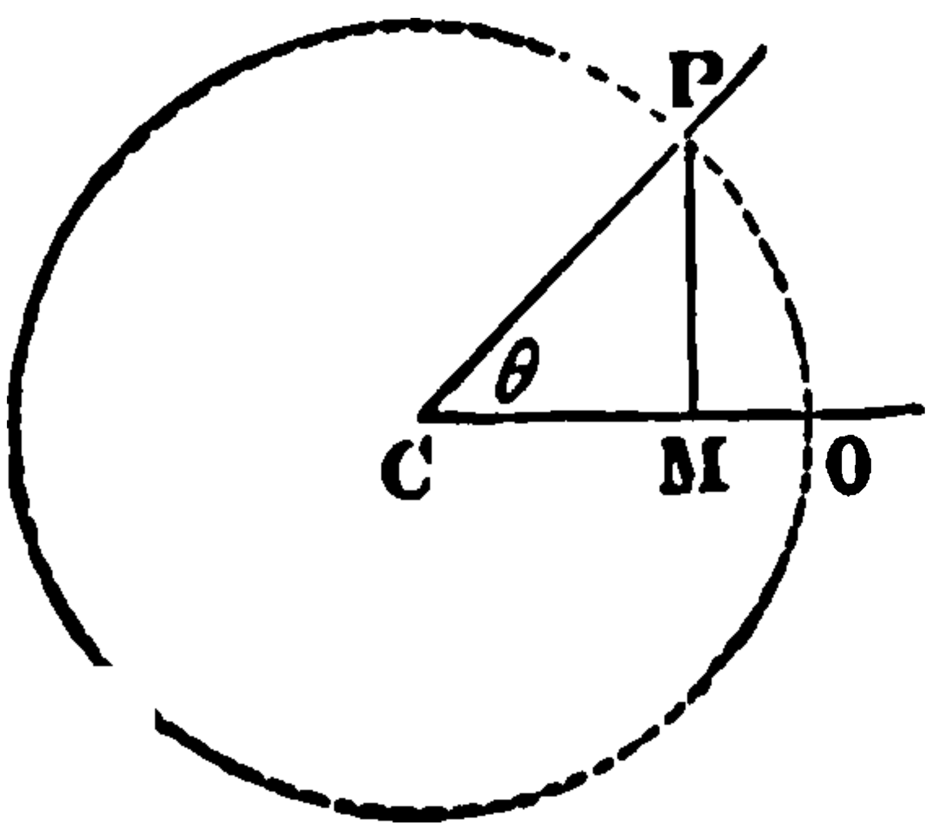


Fig. 89.

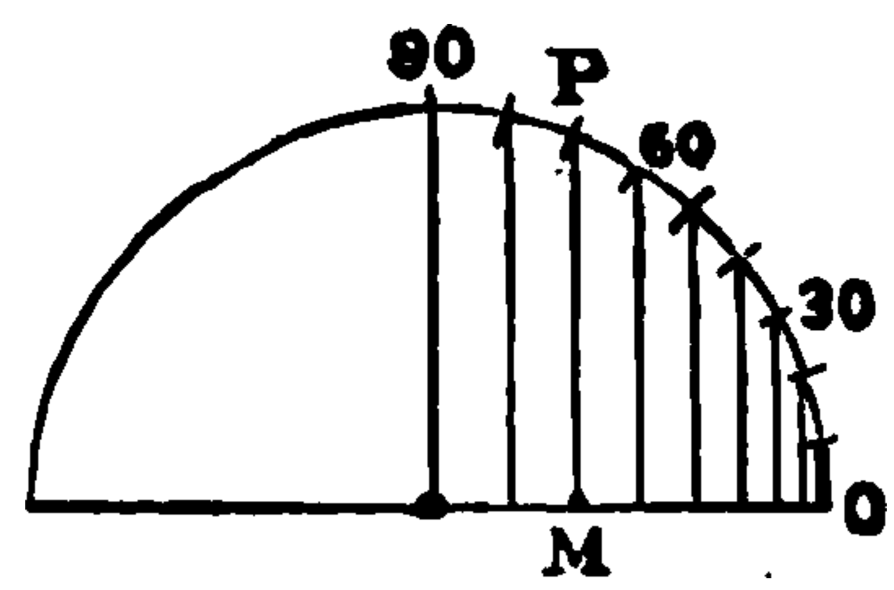


Fig. 90.

$$\text{Sin}\ \theta = \frac{\text{PM}}{\text{CP}}$$

$$\text{Cos}\ \theta = \frac{\text{CM}}{\text{CP}}.$$

147. Reckoning by Tangents. — Suppose we draw our circle as before (Fig. 91), but at the point O draw a straight line touching the circle, the *tangent line* at O; let us also prolong CP until it meets the tangent line at T. We may measure the angle between OC and OP in terms of the length of the tangent OT as compared with the length of the radius. Since our radius is 1, this ratio is numerically the length of OT, and we may therefore call the length of OT *the "tangent" of the angle* OCP. It is clear that smaller angles will have smaller tangents, but that larger angles may have very large tangents; in fact, the length of the tangent when PC was moved round to a right angle would be infinitely great. It can be shown that the ratio between the lengths of the sine and of the cosine of the angle is the same as the ratio between the length of the tangent and that of the radius; or the tangent of an angle is equal to its sine divided by its cosine. The formula for the tangent may be written:

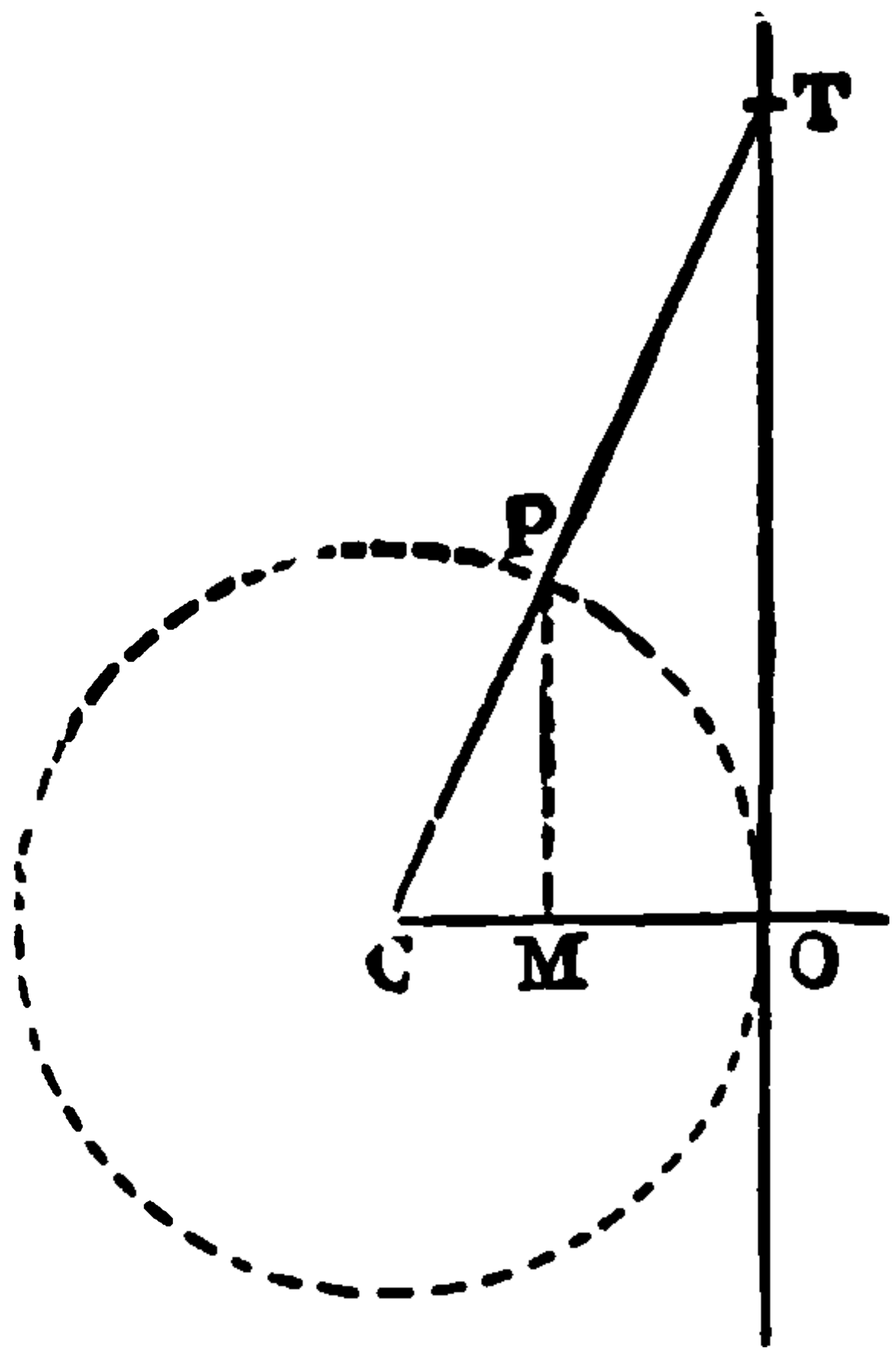


Fig. 91.

$$\tan\theta = \frac{TO}{OC} = \frac{PM}{MC}.$$

148. Solid Angles. — When three or more surfaces intersect at a point they form a *solid angle:* there is a solid angle, for example, at the top of a pyramid, or of a cone, and one at every corner of a diamond that has been cut. If a surface of any given shape be near a point, it is said to subtend a certain solid angle at that point, the solid angle being mapped out by drawing lines from all points of the edge of this surface to the point P (Fig. 92). An irregular cone will thus be generated whose solid angle is the solid angle subtended at P by the surface EF. To reckon this solid angle we adopt an expedient similar to that adopted when we wished to reckon a plane angle in radians. About the point P, with radius of 1 centimetre, describe a *sphere*, which will intercept

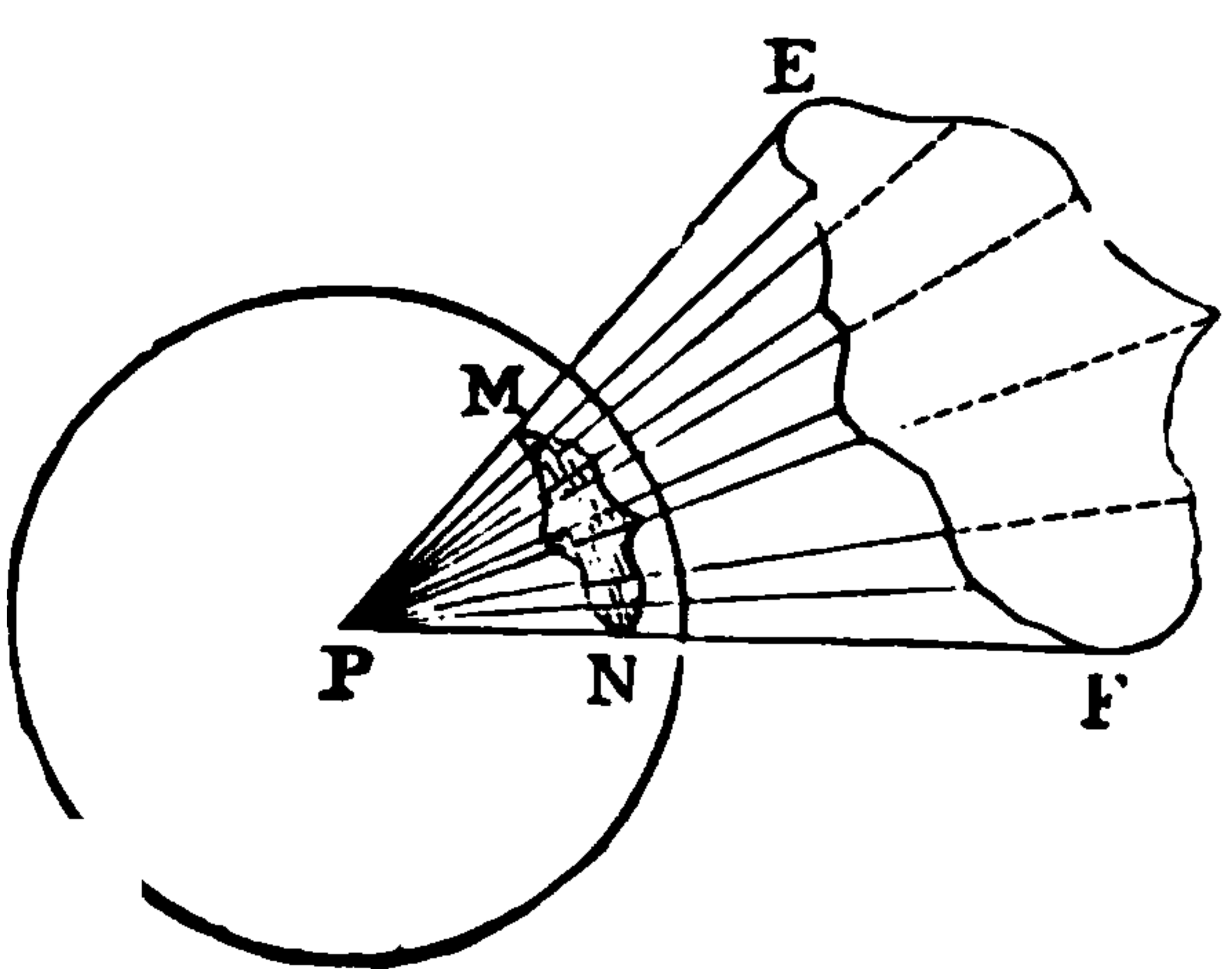


Fig. 92.

the cone over an area MN: the area thus intercepted measures the solid angle. If the sphere have the radius 1, its total surface is 4π. The solid angle subtended at the centre by a hemisphere would be 2π. It will be seen that the ratio between the area of the surface EF and the area of the surface MN is the ratio between the squares of the lines EP and MP. The solid angle subtended by a surface at a point (other things being equal) is inversely proportional to the square of its distance from the point. This is the basis of the law of inverse squares.

A table of radiaus, sines, tangents, etc., is given at the end of this book as Appendix A.

Lesson XII. — *Terrestrial Magnetism*

149. The Mariner's Compass. — It was mentioned in Art. 87 that the compass sold by opticians consists of

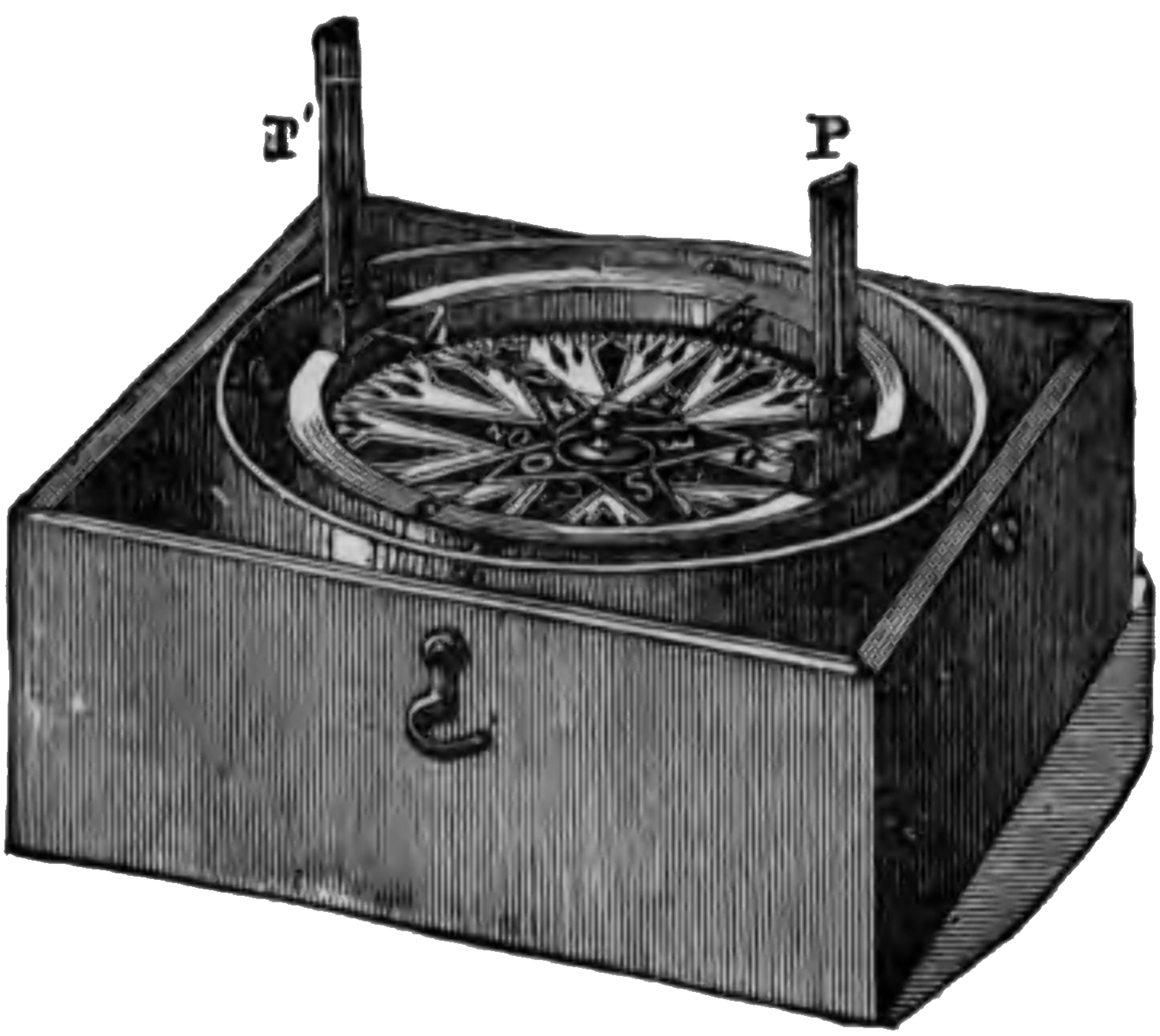


Fig. 93.

a magnetized steel needle balanced on a fine point above a card marked out N, S, E, W, etc. The **Mariner's Compass** is, however, somewhat differently arranged.

In Fig. 93 one of the forms of a Mariner's Compass,

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the geographical meridian of a place is called the magnetic **Declination** of that place. The existence of this declination was discovered by Columbus in 1492, though it appears to have been previously known to the Chinese, and is said to have been noticed in Europe in the early part of the thirteenth century by Peter Peregrinus. The fact that the declination differs at different points of the earth's surface, is the undisputed discovery of Columbus.

In order that ships may steer by the compass, magnetic charts (Art. 154) must be prepared, and the declination at different places accurately measured. The upright pieces P, P′, on the "azimuth compass" drawn in Fig. 93, are for the purpose of sighting a star whose position may be known from astronomical tables, and thus affording a comparison between the magnetic meridian of the place and the geographical meridian, and of measuring the angle between them.

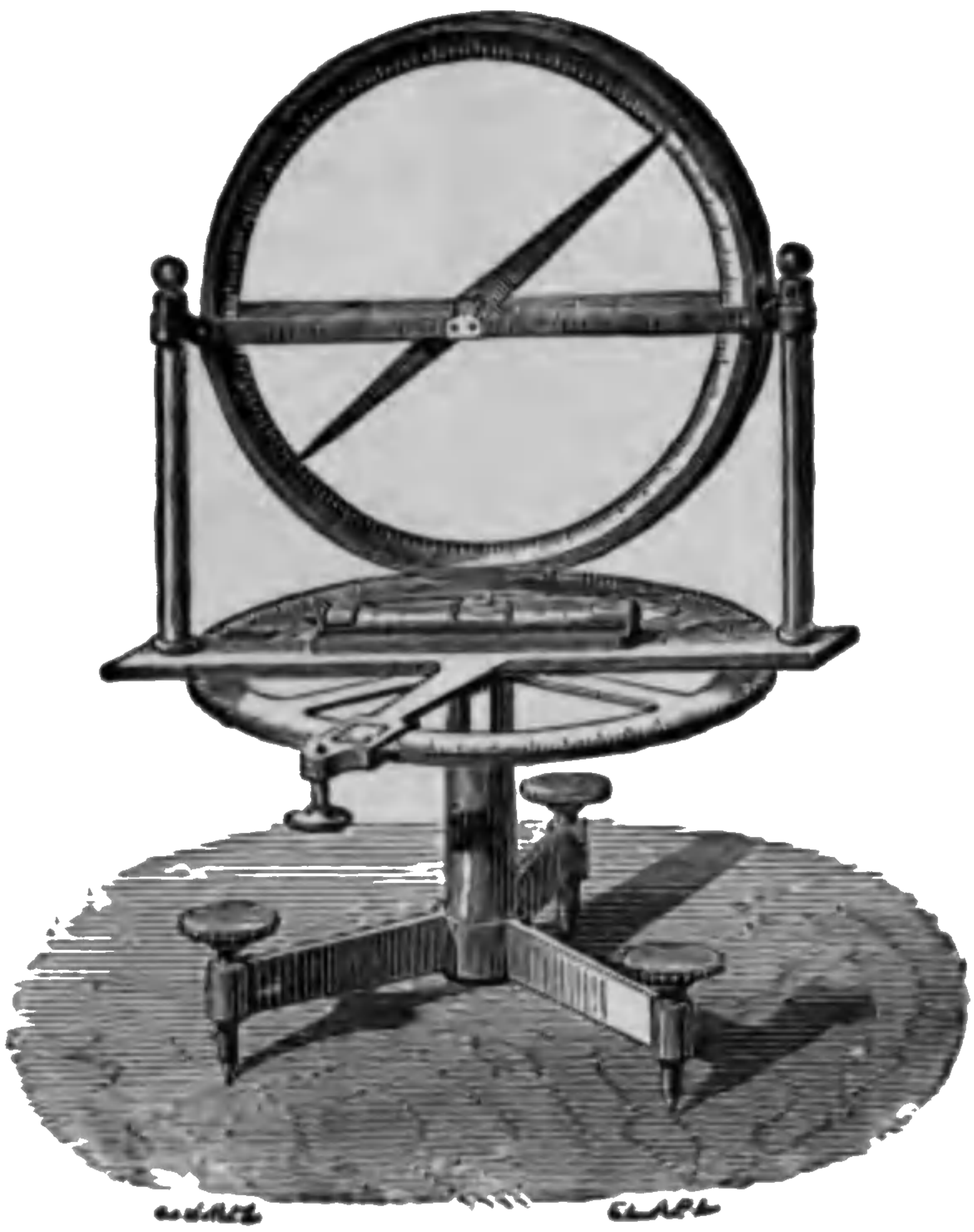


Fig. 94.

152. Inclination or Dip. — Norman, an instrument-maker, discovered in 1576 that a balanced needle, when magnetized, tends to dip downwards toward the north. He therefore constructed a **Dipping-Needle**, capable of turning in a vertical plane about a horizontal axis, with which he found the "dip" to be (at London) an

angle of 71° 50′. A simple form of dipping-needle is shown in Fig. 94. The dip-circles used in the magnetic observatory at Kew are much more exact and delicate instruments. It was, however, found that the dip, like the declination, differs at different parts of the earth's surface, and that it also undergoes changes from year to year. The "dip" in London for the year 1894 is 67° 18′; in 1900 it will be 67° 9′. At the north magnetic pole the needle dips straight down. The following table gives particulars of the Declination, Inclination, and total magnetic force at a number of important places, the values being approximately true for the year 1900.

TABLE OF MAGNETIC DECLINATION AND INCLINATION (for Year 1900)

Locality.	Declination.	Dip.	Total Force (C.G.S.).
London	16° 16′ W.	67° 9′ N.	0·47
St. Petersburg .	0° 30′ E.	70° 46′ N.	0·48
Berlin	9° 30′ W.	66° 43′ N.	0·48
Paris	14° 30′ W.	64° 55′ N.	0·47
Rome	10° 0′ W.	58° 0′ N.	0·45
New York . . .	9° 12′ W.	70° 6′ N.	0·61
Washington . .	4° 35′ W.	70° 18′ N.	0·60
San Francisco .	16° 42′ E.	62° 20′ N.	0·54
Mexico	8° 0′ E.	45° 1′ N.	0·48
St. Helena . . .	25° 0′ W.	32° 12′ S.	0·31
Cape Town . .	29° 24′ W.	58° 2′ S.	0·36
Sydney	9° 36′ E.	62° 45′ S.	0·57
Hobarton . . .	25° 0′ E.	71° 12′ S.	0·64
Bombay	0° 36′ E.	20° 38′ N.	0·37
Tokio	4° 6′ W.	49° 52′ N.	0·45

153. Intensity.—Three things must be known in order to specify exactly the magnetism at any place; these three elements are:

The Declination;
The Inclination, and
The Intensity of the Magnetic Force.

The magnetic force is measured by one of the methods mentioned in the preceding lesson. Its direction is in the line of the dipping-needle, which, like every magnet, tends to set itself along the lines of force. It is, however, more convenient to measure the force not in its total intensity in the line of the dip, but to measure the horizontal component of the force, — that is to say, the force in the direction of the horizontal compass-needle, from which the total force can be calculated if the dip is known.* Or if the horizontal and vertical components of the force are known, the total force and the angle of the dip can both be calculated.† The horizontal component of the force, or "horizontal intensity," can be ascertained either by the method of Vibrations or by the method of Deflexions. The mean horizontal force of the earth's magnetism at London in 1890 was ·1823 dyne-units, the mean vertical force ·4377, the total force (in the line of dip) was ·4741 dyne-units. The distribution of the magnetic force at different points of the earth's surface is irregular, and varies in different latitudes according to an approximate law, which, as given by Biot, is that the force is proportional to $\sqrt{1 + 3 \sin^2 l}$, where l is the magnetic latitude.

154. Magnetic Maps. — For purposes of convenience it is usual to construct magnetic maps, on which such data as these given in the Table on p. 139 can be marked down. Such maps may be constructed in several ways. Thus, it would be possible to take a map of England, or of the world, and mark it over with lines such as to represent by their direction the actual direction in which the compass points; in fact to draw the lines of force or

* For if H = Horizontal Component of Force, and I = Total Force, and θ = angle of dip, $I = H \div \cos\theta$.

† For $H^2 + V^2 = I^2$, where V = Vertical Component of Force.

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the year 1900. It has been prepared from data furnished by Professor Mendenhall of the U.S. Geodetic Survey. It will be noticed that in the year 1900 the magnetic declination will be zero at Lansing (Mich.), Columbus (Ohio), and Charleston (S. Carolina).

The line passing through places of no declination is called the *agonic* line. It passes across both hemispheres, crossing Russia, Persia, and Australia. There is another agonic line in eastern Asia enclosing a region around Japan, within which there is a westerly declination.

155. Variations of Earth's Magnetism.—We have already mentioned that both the declination and the inclination are subject to changes; some of these changes take place very slowly, others occur every year, and others again every day.

Those changes which require many years to run their course are called *secular changes*.

The variations of the *declination* previous to 1580 are not recorded; the compass at London then pointed 11° *east* of true north. This easterly declination gradually decreased, until in 1657 the compass pointed true north. It then moved westward, attaining a maximum of 24° 27′ about the year 1816, from which time it has slowly diminished to its present value (16° 57′ in 1894); it diminishes (in England) at about the rate of 7′ per year. At about the year 1976 it will again point truly north, making a complete cycle of changes in about 320 years.

The *Inclination* in 1576 was 71° 50′, and it slowly increased till 1720, when the angle of dip reached the maximum value of 74° 42′. It has since steadily diminished to its present (1894) value of 67° 39′. The period in which the cycle is completed is not known, but the rate of variation of the dip is less at the present time than it was fifty years ago. In all parts of the earth both declination and inclination are slowly changing. The following table gives the data of the secular changes at London.

Table of Secular Magnetic Variations

Year.	Declination.	Inclination.
1576		71° 50′
1580	11° 17′ E.	
1600		72° 0′
1622	6° 12′	
1634	4° 0′	
1657	0° 0′ min.	
1676	3° 0′ W.	73° 30′
1705	9° 0′	
1720	13° 0′	74° 42′ max.
1760	19° 30′	
1780		72° 8′
1800	24° 6′	70° 35′
1816	24° 30′ max.	
1830	24° 2′	69° 3′
1855	23° 0′	
1868	20° 33′	68° 2′
1878	19° 14′	67° 43′
1880	18° 40′	67° 40′
1890	17° 26′	67° 23′
1900	16° 16′	67° 9′

The *Total Magnetic Force*, or "Intensity," also slowly changes in value. As measured near London, it was equal to ·4791 dyne-units in 1848, ·4740 in 1866, in 1880 ·4736 dyne-units, in 1890 ·4741.* Owing to the steady decrease of the angle at which the needle dips, the horizontal component of this force (*i.e.* the "Horizontal Intensity") is slightly increasing. It was ·1716 dyne-units in 1814, ·1797 dyne-units at the beginning of 1880, and ·1823 dyne-units in 1890.

156. Daily Variations.—Both compass and dipping-needle, if minutely observed, exhibit slight daily mo-

* That is to say, a north magnet pole of unit strength is urged in the line of dip, with a mechanical force of a little less than half a dyne.

tions. About 7 A.M. the compass-needle begins to travel westward with a motion which lasts till about 1 P.M.; during the afternoon and evening the needle slowly travels back eastward, until about 10 P.M.; after this it rests quiet; but in summer-time the needle begins to move again slightly to the west at about midnight, and returns again eastward before 7 A.M. These delicate variations—never more than 10′ of arc—appear to be connected with the position of the sun; and the moon also exercises a minute influence upon the position of the needle.

157. Annual Variations.—There is also an annual variation corresponding with the movement of the earth around the sun. In the British Islands the total force is greatest in June and least in February, but in the Southern Hemisphere, in Tasmania, the reverse is the case. The dip also differs with the season of the year, the angle of dip being (in England) less during the four summer months than in the rest of the year.

158. Eleven-Year Period.—General Sabine discovered that there is a larger amount of variation of the declination occurring about once every eleven years. Schwabe noticed that the recurrence of these periods coincided with the eleven-year periods at which there is a maximum of *spots* on the sun. Professor Balfour Stewart and others have endeavoured to trace a similar periodicity in the recurrence of **auroræ** * and of other phenomena.

159. Magnetic Storms.—It is sometimes observed that a sudden (though very minute) irregular disturbance will affect the whole of the compass-needles over a considerable region of the globe. Such occurrences are known as magnetic storms; they frequently occur at the time when an aurora is visible.

160. Self-recording Magnetic Apparatus.—At Kew and other magnetic observatories the daily and hourly

* See Lesson XXIV., on Atmospheric Electricity.

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for accounting for the growth of the earth's magnetism to its present state. The action of the sun and moon in raising tides in the atmosphere might account for the variations mentioned in Art. 155. It is important to note that in all magnetic storms the intensity of the perturbations is greatest in the regions nearest the poles; also, that the magnetic poles coincide very nearly with the regions of greatest cold; that the region where auroræ (Art. 336) are seen in greatest abundance is a region lying nearly symmetrically round the magnetic pole. It may be added that the general direction of the feeble daily earth-currents (Art. 233) is from the poles toward the equator.

CHAPTER III

CURRENT ELECTRICITY

Lesson XIII. — *Simple Voltaic Cells*

162. Flow of Currents. — It has been already mentioned, in Lesson IV., how electricity flows away from a charged body through any conducting substance, such as a wire or a wetted string. If, by any arrangement, electricity could be supplied to the body just as fast as it flowed away, a continuous current would be produced. Such a current always flows through a conducting wire, if the ends are kept at different electric potentials. In like manner, a current of heat flows through a rod of metal if the ends are kept at different temperatures, the flow being always from the high temperature to the lower. No exact evidence exists as to the direction in which the current in a wire really "flows." It is convenient to regard the electricity as flowing from positive to negative; or, in other words, the natural direction of an electric current is from the high potential to the low. It is obvious that such a flow tends to bring both to one level of potential. In order that a continuous flow may be kept up there must be a *circuit* provided. The "current" has sometimes been regarded as a double transfer of positive electricity in one direction, and of negative electricity in the opposite direction. The only evidence to support this very unnecessary supposition

is the fact that, in the decomposition of liquids by the current, some of the elements are liberated at the place where the current enters, others at the place where it leaves the liquid.

The quantity of electricity conveyed by a current is proportional to the current and to the time that it continues to flow. The practical unit of current is called the *ampere* (see Arts. 207 and 254). The quantity of electricity conveyed by a current of one *ampere* in one second is called one *ampere-second* or one *coulomb*. One *ampere-hour* equals 3600 *coulombs*. If C is the number of amperes of current, t the number of seconds that it lasts, and Q the number of coulombs of electricity thereby conveyed, the relation between them is expressed by the formula:—

$$Q = C \times t.$$

Example.—If a current of 80 amperes flows for 15 minutes the total quantity of electricity conveyed will be $80 \times 15 \times 60 = 72{,}000$ coulombs. This is equal to 20 ampere-hours.

Currents are called *continuous* if they flow, without stopping, in one direction. They are called *alternate currents* if they continually reverse in direction in a regular periodic manner, flowing first in one direction round the circuit and then in the other.

Continuous currents of electricity, such as we have described, are produced by *voltaic cells*, and *batteries* of such cells, or else by *dynamos* driven by power, though there are other sources of currents hereafter to be mentioned. Alternate currents are produced by special alternate current dynamos or *alternators*, and are separately treated of in Art. 470.

163. Discoveries of Galvani and of Volta.—The discovery of electric currents originated with *Galvani*, a physician of Bologna, who, about the year 1786, made a series of curious and important observations upon the

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enough to give quite a perceptible shock, if the top and bottom disks, or wires connected with them, be touched simultaneously with the moist fingers. When a single pair of metals are placed in contact, one becomes + ly electrical to a certain small extent, and the other – ly electrical, or, in other words, there is a certain difference of electric potential (see Art. 265) between them. But when a number are thus set in series with moist conductors between the successive pairs, the difference of potential between the first zinc and the last copper disk is increased in proportion to the number of pairs; for now all the successive small differences of potential are added together.

165. The Crown of Cups. — Another combination devised by Volta was his *Couronne de Tasses* or *Crown of Cups.* It consisted of a number of cups (Fig. 96), filled either with brine or dilute acid, into which dipped a number of compound strips, half zinc, half copper, the zinc portion of one strip dipping into one cup, while

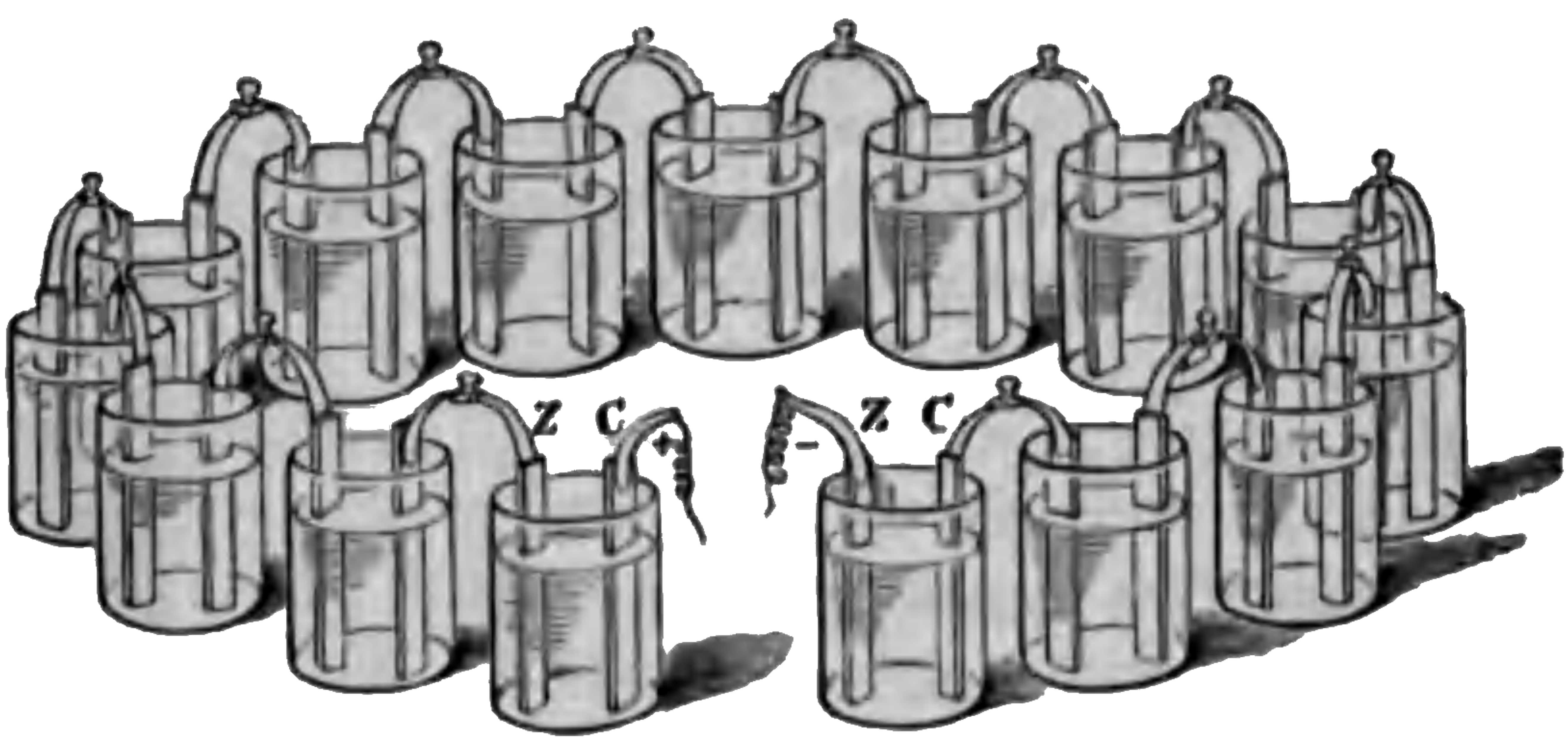


Fig. 96.

the copper portion dipped into the other cup. The difference of potential between the first and last cups is again proportional to the number of pairs of metal strips. This arrangement, though badly adapted for such a purpose, is powerful enough to ring an electric bell, the wires of which are joined to the first zinc and the last copper strip. The electrical action of these

combinations is, however, best understood by studying the phenomena of one single cup or *cell.*

166. Simple Voltaic Cell. — Place in a glass jar some water having a little sulphuric acid or any other oxidizing acid added to it (Fig. 97). Place in it separately two clean strips, one of zinc Z, and one of copper C. This cell is capable of supplying a continuous flow of electricity through a wire whose ends are brought into connexion with the two strips. When the current flows the zinc strip is observed to waste away; its consumption in fact furnishes the energy required to drive the current through the cell and the connecting wire.

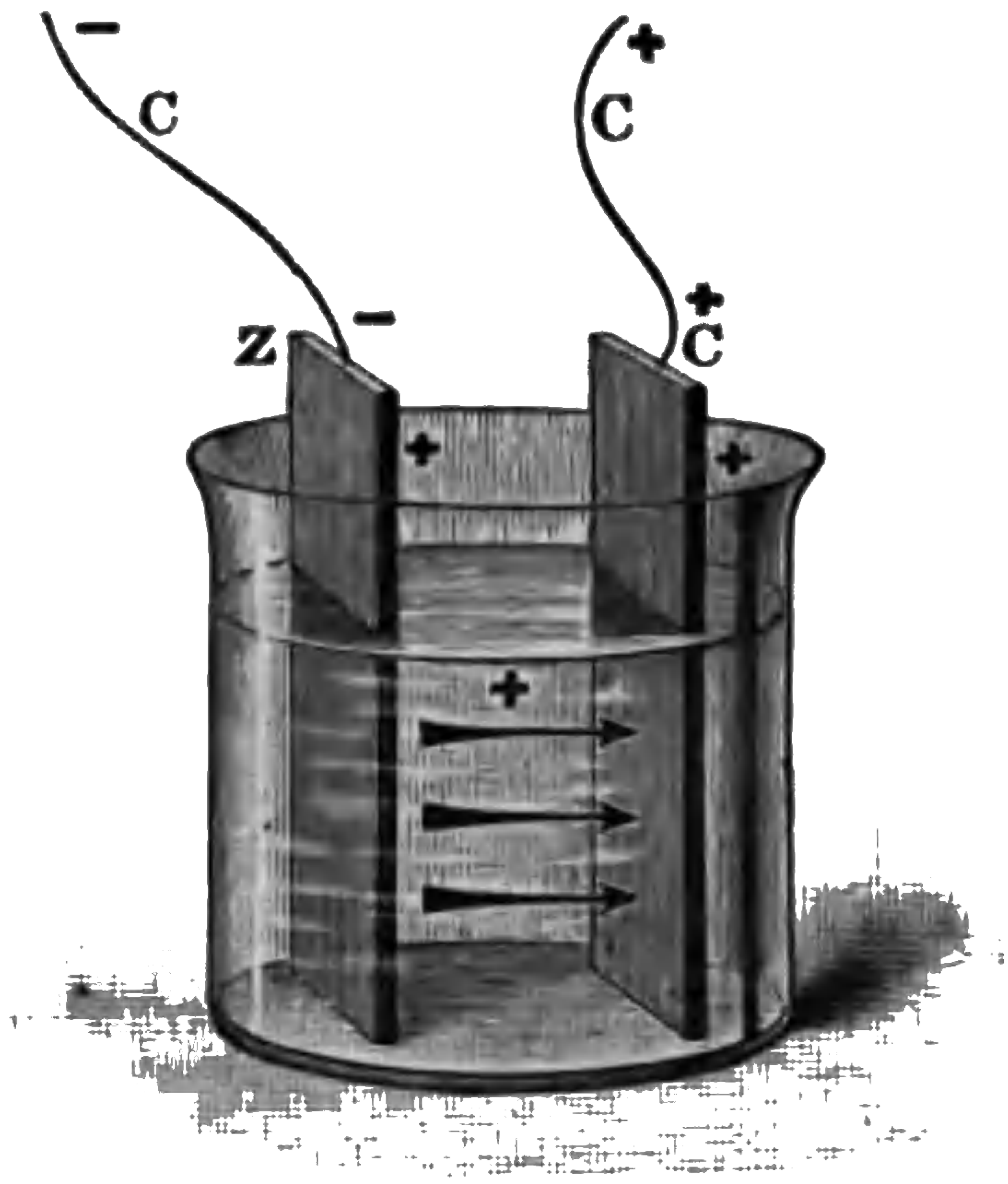


Fig. 97.

The cell may therefore be regarded as a sort of chemical furnace in which fuel is consumed to drive the current. The zinc is the fuel,* the acid is the aliment, whilst the copper is merely a metallic hand let down into the cell to pick up the current, and takes no part chemically. Before the strips are connected by a wire no appreciable difference of potential between the copper and the zinc will be observed by an electrometer; because the electrometer only measures the potential at a point in the air or oxidizing medium outside the zinc or the copper, not the

* Zinc, as is well known, will burn with a blue flame in air or oxygen, giving out heat. Zinc foil is easily kindled.

potentials of the metals themselves. The zinc is trying to dissolve and throw a current across to the copper; while the copper is trying (less powerfully) to dissolve and throw a current across the other way. The zinc itself is at about 1·86 volts higher potential than the surrounding oxidizing media (see Art. 489); while the copper is at only about ·81 volts higher, having a less tendency to become oxidized. There is then a latent difference of potential of about 1·05 volts between the zinc and the copper; but this produces no current as long as there is no metallic circuit. If the strips are made to touch, or are joined by a pair of metal wires, immediately there is a rush of electricity through the acid from the zinc to the copper, as indicated by the arrows in Fig. 97, the current returning by the metal circuit from the copper to the zinc. A small portion of the zinc is at the same time dissolved away; the zinc parting with its latent energy as its atoms combine with the acid. This energy is expended in forcing electricity through the acid to the copper strip, and thence through the wire circuit back to the zinc strip. The copper strip, whence the current starts on its journey through the external circuit, is called the *positive pole*, and the zinc strip is called the *negative pole.* If two copper wires are united to the tops of the two strips, though no current flows so long as the wires are kept separate, the wire attached to the zinc will be found to be negative, and that attached to the copper positive, there being still a *tendency* for the zinc to oxidize and drive electricity through the cell from zinc to copper. This state of things is represented by the + and – signs in Fig. 97; and this distribution of potentials led some to consider the junction of the zinc with the copper wire as the starting point of the current. But the real starting point is in the cell at the surface of the zinc where the chemical action is furnishing energy; for from this point there are propagated through the liquid certain electro-chemical actions (more fully ex-


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many ways of grouping a battery of cells, but two need special notice. If the cells are joined up in one row, as in Fig. 96 or Fig. 98, they are said to be *in series*. Electricians often represent a cell by a symbol in which a short thick line stands for the zinc and a longer thin line for the copper (or carbon). Thus Fig. 98 represents four cells joined in series. So joined they do not yield more current (more *amperes*) than a single cell would yield, but they yield that current with a fourfold electromotive force (*i.e.* with more *volts* of pressure).



Fig. 98.

The other chief way of grouping cells is to join all the zincs together and all the coppers (or carbons) together; and they are then said to be *in parallel*, or are joined "for quantity." So joined they have no greater electromotive-force than one cell. The zincs act like one big zinc, the coppers like one big copper. But they will yield more current. Fig. 99 shows the four cells grouped *in parallel;* they would yield thus a current four times as great as one cell alone would yield.

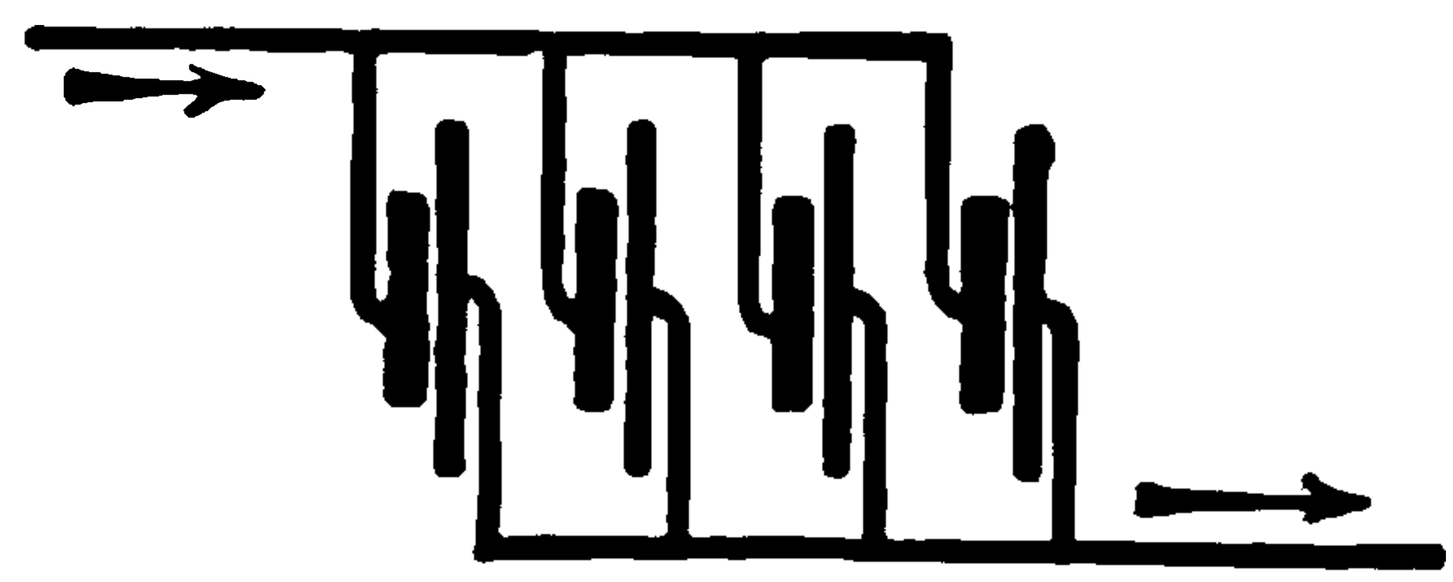


Fig. 99.

169. Electromotive-Force.—The term *electromotive-force* is employed to denote that which moves or tends to move electricity from one place to another.* For

Electricity, or sometimes even *Galvanism* (!), but, as we shall see, it differs only in degree from Frictional or any other Electricity, and both can flow along wires, and magnetize iron, and decompose chemical compounds. The word *Battery* means an arrangement of one or more cells; just as in warfare a battery of guns means an arrangement of one or more.

* The beginner must not confuse *Electromotive-force*, or that which tends to move electricity, with *Electric "force,"* or that force with which electricity tends to move matter. Newton has virtually defined "force," once for all, as that which moves or tends to move matter. When matter is moved by a magnet we speak rightly of *magnetic force;* when electricity

brevity we sometimes write it E.M.F. In this particular case it is obviously the result of the difference of potential, and proportional to it. Just as in water-pipes a *difference of level* produces a *pressure*, and the pressure produces a *flow* so soon as the tap is turned on, so *difference of potential* produces *electromotive-force*, and electromotive-force sets up a *current* so soon as a circuit is completed for the electricity to flow through. Electromotive-force, therefore, may often be conveniently expressed as a difference of potential, and *vice versâ;* but the student must not forget the distinction. The unit in which electromotive-force is measured is termed the *volt* (see Art. 354). The terms *pressure* and *voltage* are sometimes used for difference of potential or electromotive-force.

170 Volta's Laws. — Volta showed (Art. 79) that the difference of potential between two metals in contact (in air) depended merely on what metals they were, not on their size, nor on the amount of surface in contact. He also showed that when a number of metals touched one another the difference of potential between the first and last of the row is the same as if they touched one another directly. A quantitative illustration from the researches of Ayrton and Perry was given in Art. 80. But the case of a series of cells is different from that of a mere row of metals in contact. If in the row of cells the zincs and coppers are all arranged in one order, so that all of them set up electromotive-forces in the same direction, *the total electromotive-force of the series will be equal to the electromotive-force of one cell multiplied by the number of cells.*

Hitherto we have spoken only of zinc and copper as the materials for a cell; but cells may be made of any two metals. The effective electromotive-force of a cell depends on the *difference* between the two. If zinc was

moves matter we may speak of *electric force.* But E.M.F. is quite a different thing, not "force" at all, for it acts not on matter but on electricity, and tends to move it.

used for both metals in a cell it would give no current, for each plate would be trying to dissolve and to throw a current across to the other with equal tendency. That cell will have the greatest electromotive-force or be the most "intense," in which those materials are used which have the greatest difference in their tendency to combine chemically with the acid, or which are widest apart on the "contact-series" given in Art. 80. Zinc and copper are convenient in this respect; and zinc and silver would be better but for the expense. For more powerful batteries a zinc-platinum or a zinc-carbon combination is preferable. That plate or piece of metal in a cell by which the current enters the liquid is called the *anode;* it is that plate which dissolves away. The plate or piece of metal by which the current leaves the cell is called the *kathode;* it is not dissolved, and in some cases receives a deposit on its surface.

171. **Resistance.** — The same electromotive-force does not, however, always produce a current of the same *strength.* The amount of current depends not only on the force tending to drive the electricity round the circuit, but also on the **resistance** which it has to encounter and overcome in its flow. If the cells be partly choked with sand or sawdust (as is sometimes done in so-called "Sawdust Batteries" to prevent spilling), or, if the wire provided to complete the circuit be very long or very thin, the action will be partly stopped, and the current will be weaker, although the E.M.F. may be unchanged. The analogy of the water-pipes will again help us. The pressure which forces the water through pipes depends upon the difference of level between the cistern from which the water flows and the tap to which it flows; but the amount of water that runs through will depend not on the pressure alone, but on the resistance it meets with; for, if the pipe be a very thin one, or choked with sand or sawdust, the water will only run slowly through.

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Probably both result from a common cause (see Art. 80, and also 480). A piece of quite pure zinc when dipped alone into dilute sulphuric acid is not attacked by the liquid. But the ordinary commercial zinc is not pure, and when plunged into dilute sulphuric acid dissolves away, a large quantity of bubbles of hydrogen gas being given off from the surface of the metal. Sulphuric acid is a complex substance, in which every molecule is made up of a group of atoms — 2 of Hydrogen, 1 of Sulphur, and 4 of Oxygen; or, in symbols, H_2SO_4. The chemical reaction by which the zinc enters into combination with the radical of the acid, turning out the hydrogen, is expressed in the following equation: —

$$\underset{\text{Zinc}}{Zn} \underset{\text{and}}{+} \underset{\text{Sulphuric Acid}}{H_2SO_4} \underset{\text{produce}}{=} \underset{\text{Sulphate of Zinc}}{ZnSO_4} \underset{\text{and}}{+} \underset{\text{Hydrogen.}}{H_2}$$

The sulphate of zinc produced in this reaction remains in solution in the liquid.

Now, when a plate of pure zinc and a plate of some less-easily oxidizable metal — copper or platinum, or, best of all, carbon (the hard carbon from gas retorts) — are put side by side into the cell containing acid, no appreciable chemical action takes place until the circuit is completed by joining the two plates with a wire, or by making them touch one another. Directly the circuit is completed a current flows and the chemical actions begin, the zinc dissolving in the acid, and the acid giving up its hydrogen in streams of bubbles. But it will be noticed that these bubbles of hydrogen are evolved *not* at the zinc plate, nor yet throughout the liquid, but *at the surface of the copper plate* (or the carbon plate if carbon is employed). This apparent transfer of the hydrogen gas through the liquid from the surface of the zinc plate to the surface of the copper plate where it appears is very remarkable. The ingenious theory framed by Grotthuss to account for it, is explained in Lesson XLVII. on Electro-Chemistry.

These chemical actions go on as long as the current passes. The quantity of zinc used up *in each cell* is proportional to the amount of electricity which flows round the circuit while the battery is at work; or, in other words, is proportional to the current. The quantity of hydrogen gas evolved is also proportional to the amount of zinc consumed, and also to the current. After the acid has thus dissolved zinc in it, it will no longer act as a corrosive solvent; it has been "killed," as workmen say, for it has been turned into sulphate of zinc. The battery will cease to act, therefore, either when the zinc has all dissolved away, or when the acid has become exhausted, that is to say, when it is all turned into sulphate of zinc. Stout zinc plates will last a long time, but the acids require to be renewed frequently, the spent liquor being emptied out.

173. Local Action.—When the circuit is not closed the current cannot flow, and there should be no chemical action so long as the battery is producing no current. The impure zinc of commerce, however, does not remain quiescent in the acid, but is continually dissolving and giving off hydrogen bubbles. This local action, as it is termed, is explained in the following manner:—The impurities in the zinc consist of particles of iron, arsenic, and other metals. Suppose a particle of iron to be on the surface anywhere and in contact with the acid. It will behave like the copper plate of a battery towards the zinc particles in its neighbourhood, for a local difference of potential will be set up at the point where there is metallic contact, causing a local or parasitic current to run from the particles of zinc through the acid to the particle of iron, and so there will be a continual wasting of the zinc, both when the battery circuit is closed and when it is open.

174. Amalgamation of Zinc.—We see now why a piece of ordinary commerical zinc is attacked on being placed in acid. There is local action set up all over its

surface in consequence of the metallic impurities in it. To do away with this local action, and abolish the wasting of the zinc while the battery is at rest, it is usual to **amalgamate** the surface of the zinc plates with mercury. The surface to be amalgamated should be cleaned by dipping into acid, and then a few drops of mercury should be poured over the surface and rubbed into it with a bit of linen rag tied to a stick. The mercury unites with the zinc at the surface, forming a pasty amalgam.. The iron particles do not dissolve in the mercury, but float up to the surface, whence the hydrogen bubbles which may form speedily carry them off. As the zinc in this pasty amalgam dissolves into the acid the film of mercury unites with fresh portions of zinc, and so presents always a clean bright surface to the liquid.

A newer and better process is to add about 4 per cent of mercury to the molten zinc before casting into plates or rods. If the zinc plates of a battery are well amalgamated there should be no evolution of hydrogen bubbles when the circuit is open. Nevertheless there is still always a little wasteful local action during the action of the battery. Jacobi found that while one part of hydrogen was devolved at the kathode, 33·6 parts of zinc were dissolved at the anode, instead of the 32·5 parts which are the chemical equivalent of the hydrogen.

175. Polarization.—The bubbles of hydrogen gas liberated at the surface of the copper plate stick to it in great numbers, and form a film over its surface; hence the effective amount of surface of the copper plate is very seriously reduced in a short time. When a simple cell, or battery of such cells, is set to produce a current, it is found that the current after a few minutes, or even seconds, falls off very greatly, and may even be almost stopped. This immediate falling off in the current, which can be observed with any galvanometer and a pair of zinc and copper plates dipping into acid, is

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plate, having its surface thus covered with a rough coating of finely divided platinum, gave up the hydrogen bubbles freely; nevertheless, in a battery of Smee Cells the current diminishes greatly after a few minutes.

2. *Chemical Means.* — If a highly-oxidizing substance be added to the acid it will destroy the hydrogen bubbles whilst they are still in the nascent state, and thus will prevent both the increased internal resistance and the opposing electromotive-force. Such substances are bichromate of potash, nitric acid, and chlorine.

3. *Electrochemical Means.* — It is possible by employing double cells, as explained in the next lesson, to so arrange matters that some solid metal, such as *copper*, shall be liberated instead of hydrogen bubbles, at the point where the current leaves the liquid. This electrochemical exchange entirely obviates polarization.

178. Simple Laws of Chemical Action in the Cell. — We will conclude this section by enumerating the two simple laws of chemical action in the cell.

I. *The amount of chemical action in the cell is proportional to the quantity of electricity that passes through it* — that is to say, is proportional to *the current* while it passes.

A current of one *ampere* flowing through the cell for one second causes 0·00033698 (or $\frac{1}{2967}$) of a gramme of zinc to dissolve in the acid, and liberates 0·000010384 (or $\frac{1}{96302}$) of a gramme of hydrogen.

II. *The amount of chemical action is equal in each cell of a battery consisting of cells joined in series.*

The first of these laws was thought by Faraday, who discovered it, to disprove Volta's contact theory. He foresaw that the principle of the conservation of energy would preclude a mere contact force from furnishing a continuous supply of current, and hence ascribed the current to the chemical actions which were proportional in quantity to it. How the views of Volta and Faraday are to be harmonized has been indicated in the last

paragraph of Art. 80. These laws only relate to the useful chemical action, and do not include the waste of "local" actions (Art. 166) due to parasitic currents set up by impurities.

LESSON XV. — *Voltaic Cells*

179. A good Voltaic Cell should fulfil all or most of the following conditions: —

1. Its electromotive-force should be high and constant.
2. Its internal resistance should be small.
3. It should give a constant current, and therefore must be free from polarization, and not liable to rapid exhaustion, requiring frequent renewal of the acid.
4. It should be perfectly quiescent when the circuit is open.
5. It should be cheap and of durable materials.
6. It should be manageable, and if possible, should not emit corrosive fumes.

No single cell fulfils all these conditions, however, and some cells are better for one purpose and some for another. Thus, for telegraphing through a long line of wire a considerable internal resistance in the battery is no great disadvantage; while, for producing an electric light, much internal resistance is absolutely fatal. The electromotive-force of a battery depends on the materials of the cell, and on the number of cells linked together, and a high E.M.F. can therefore be gained by choosing the right substances and by taking a large number of cells. The resistance within the cell can be diminished by increasing the size of the plates, by bringing them near together, so that the thickness of the liquid between them may be as small as possible, and by choosing liquids that are good conductors.

180. Classification of Cells. — Of the innumerable forms of cells that have been invented, only those of first importance can be described. Cells are sometimes classified into two groups, according as they contain one or two fluids, or electrolytes, but a better classification is that adopted in Art. 177, depending on the means of preventing polarization.

Class I. — With Mechanical Depolarization.
(Single Fluid.)

The simple cell of Volta, with its zinc and copper plates, has been already described. The larger the copper plate, the longer time does it take to polarize. Cruickshank suggested to place the plates vertically in a trough, producing a more powerful combination. Dr. Wollaston proposed to use a plate of copper of double size, bent round so as to approach the zinc on both sides, thus diminishing the resistance, and allowing the hydrogen more surface to deposit upon. Smee, as we have seen, replaced the copper plate by platinized silver, and Walker suggested the use of plates of hard carbon instead of copper or silver, thereby saving cost, and at the same time increasing the electromotive-force. The roughness of the surface facilitates the escape of hydrogen bubbles. By agitating such cells, or raising their kathode plates for a few moments into the air, their power is partially restored. The Law cell, used in the United States for open-circuit work, is of this class: it has a small rod of zinc and a cleft cylinder of carbon of large surface immersed in solution of salammoniac.

Class II. — With Chemical Depolarization.

In these cells, in addition to the dilute acid or other *excitant* to dissolve the zinc, there is added some more

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paper allow the electric current to flow while keeping the liquids apart. In one compartment is the zinc anode dipping into its aliment of dilute acid: in the other compartment the carbon (or platinum) kathode dipping into the depolarizer. Such cells are termed *two-fluid cells.* In the case of solid depolarizers such as black oxide of manganese, oxide of copper, etc., the material merely needs to be held up to the kathode. All solid depolarizers are *slow* in acting.

Class III. — With Electrochemical Depolarization.

When any soluble metal is immersed in a solution of its own salt — for example, zinc dipped into sulphate of zinc, or copper into sulphate of copper — there is a definite electromotive-force between it and its solution, the measure of its tendency to dissolve. If a current is sent from metal to solution some of the metal dissolves; if, however, the current is sent from solution to metal some more metal will be deposited (or "plated") out of the solution. But as long as the chemical nature of the surface and of the liquid is unchanged there will be no change in the electromotive-force at the surface. It follows that if a cell were made with two metals, each dipping into a solution of its own salt, the two solutions being kept apart by a porous partition, such a cell would never change its electromotive-force. The anode would not polarize where it dissolves into the excitant; the kathode would not polarize, since it receives merely an additional thickness of the same sort as itself. This electrochemical method of avoiding polarization was discovered by Daniell. It is the principle not only of the Daniell cell, but of the Clark cell and of others. For perfect constancy the two salts used should be salts of the same acid, both sulphates, or both chlorides, for example.

181. **Daniell's Cell.** — Each cell or "element" of

Daniell's battery has an inner porous cell or partition to keep the separate liquids from mixing. The outer cell (Fig. 101) is usually of copper, and serves also as a copper kathode. Within it is placed a cylindrical cell of unglazed porous ware (a cell of parchment, or even of brown paper, will answer), and in this is a rod of amalgamated zinc as anode. The liquid in the inner cell is dilute sulphuric acid or dilute sulphate of zinc; that in the outer cell is a saturated solution of sulphate of copper ("blue vitriol"), some spare crystals of the same substance being contained in a perforated shelf at the top of the cell, in order that they may dissolve and replace that which is used up while the battery is in action.

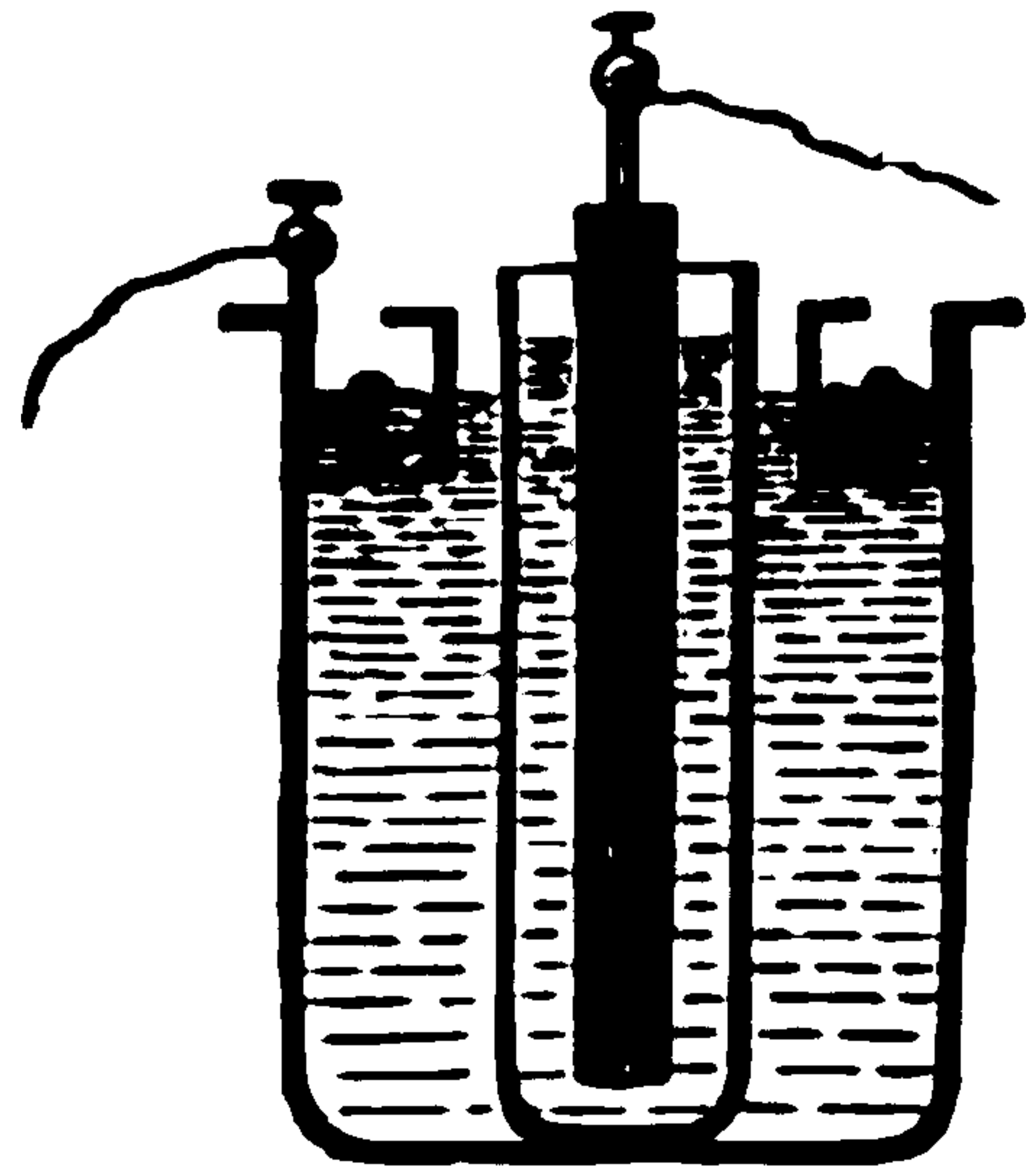


Fig. 101.

When the circuit is closed the zinc dissolves in the dilute acid, forming sulphate of zinc, and liberating hydrogen; but this gas does *not* appear in bubbles on the surface of the copper cell, for, since the inner cell is porous, the molecular actions (by which the freed atoms of hydrogen are, as explained by Fig. 266, handed on through the acid) traverse the pores of the inner cell, and there, in the solution of sulphate of copper, the hydrogen atoms are exchanged for copper atoms, the result being that pure copper, and not hydrogen gas, is deposited on the outer copper plate. Chemically these actions may be represented as taking place in two stages.

$$Zn + H_2SO_4 = ZnSO_4 + H_2$$

Zinc and Sulphuric Acid produce Sulphate of Zinc and Hydrogen.

And then

$$H_2 + CuSO_4 = H_2SO_4 + Cu.$$

Hydrogen and Sulphate of Copper produce Sulphuric Acid and Copper.

The hydrogen is, as it were, translated electrochemically into copper during the round of changes, and so while the zinc dissolves away the copper grows, the dilute sulphuric acid gradually changing into sulphate of zinc, and the sulphate of copper into sulphuric acid. In the case in which a solution of sulphate of zinc is used there is no need to consider any hydrogen atoms, copper being exchanged chemically for zinc. There is therefore no polarization so long as the copper solution is saturated; and the cell is very constant, though not so constant in all cases as Clark's standard cell described in Art. 188, owing to slight variations in the electromotive-force as the composition of the other fluid varies. When sulphuric acid diluted with twelve parts of water is used the E.M.F. is 1·178 volts. The E.M.F. is 1·07 volts when concentrated zinc sulphate is used; 1·1 volts when a half-concentrated solution of zinc sulphate is used; and, in the common cells made up with water or dilute acid, 1·1 volts or less. Owing to its constancy, this battery, made up in a convenient flat form (Fig. 106), has been much used in telegraphy. It is indispensable in those "closed circuit" methods of telegraphy (Art. 500), where the current is kept always flowing until interrupted by signalling.

182. Grove's Cell.—Sir William Grove devised a form of cell having both higher voltage and smaller internal resistance than Daniell's cell. In Grove's element there is an outer cell of glazed ware or of ebonite, containing the amalgamated zinc plate and dilute sulphuric acid. In the inner porous cell a piece of platinum foil serves as the negative pole, and it dips into the strongest nitric acid. There is no polarization in this cell, for the hydrogen liberated by the solution of the zinc in dilute sulphuric acid, in passing through the nitric acid in order to appear at the platinum pole, decomposes the nitric acid and is itself oxidized, producing water and the red fumes of nitric peroxide gas. This

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the carbon of one cell to the zinc of the next. The top part of the carbon is sometimes impregnated with paraffin wax to keep the acid from creeping up, and electrotyped with copper. Fig. 103 shows the usual way of coupling up a series of five such cells. The Bunsen's battery will continue to furnish a current for a longer time than the flat Grove's cells, on account of the larger quantity of acid contained by the cylindrical pots.*

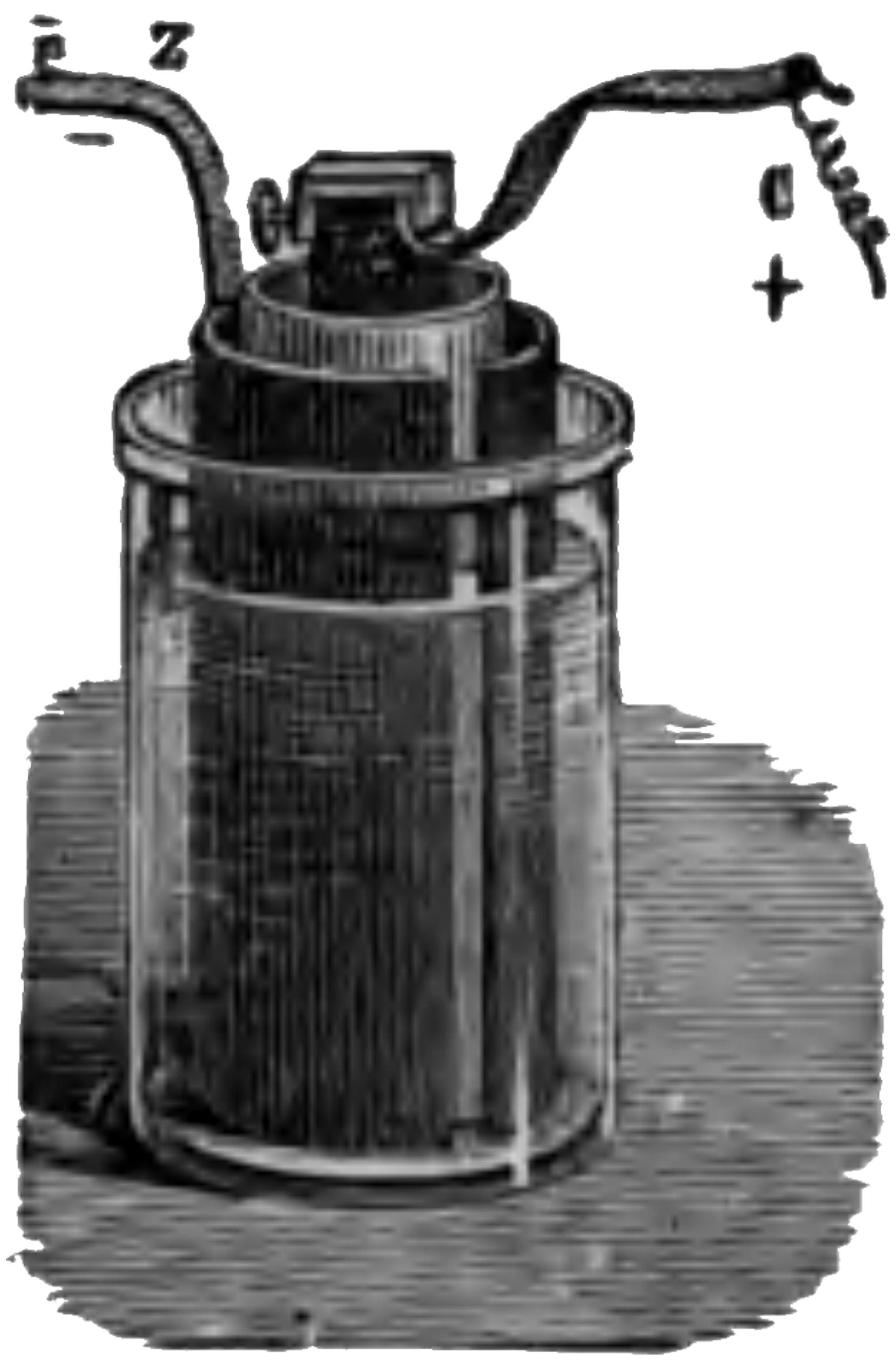


Fig. 102.

Chromic solutions, formed by adding strong sulphuric acid to solutions of bichromate of potash or of soda, are often used instead of nitric acid, in cells of this form. Soluble



Fig. 103.

depolarizers in the form of chromic powders are made by heating strong sulphuric acid and gradually stirring into it powdered bichromate of soda. The pasty mass is then cooled and powdered.

* Callan constructed a large battery in which *cast-iron* formed the positive pole, being immersed in strong nitric acid, the zincs dipping into dilute acid. The iron under these circumstances is not acted upon by the acid, but assumes a so-called "passive state." In this condition its surface appears to be impregnated with a film of magnetic peroxide, or of oxygen.

184. Leclanché's Cell. — For working electric bells and telephones, and also to a limited extent in telegraphy, a zinc-carbon cell is employed, invented by Leclanché, in which the exciting liquid is not dilute acid, but a solution of salammoniac. In this the zinc dissolves, forming a double chloride of zinc and ammonia, while ammonia gas and hydrogen are liberated at the carbon pole. The depolarizer is the black binoxide of manganese, fragments of which, mixed with powdered carbon, are held up to the carbon kathode either by packing them together inside a porous pot or by being attached as an agglomerated block. The oxide of manganese will slowly

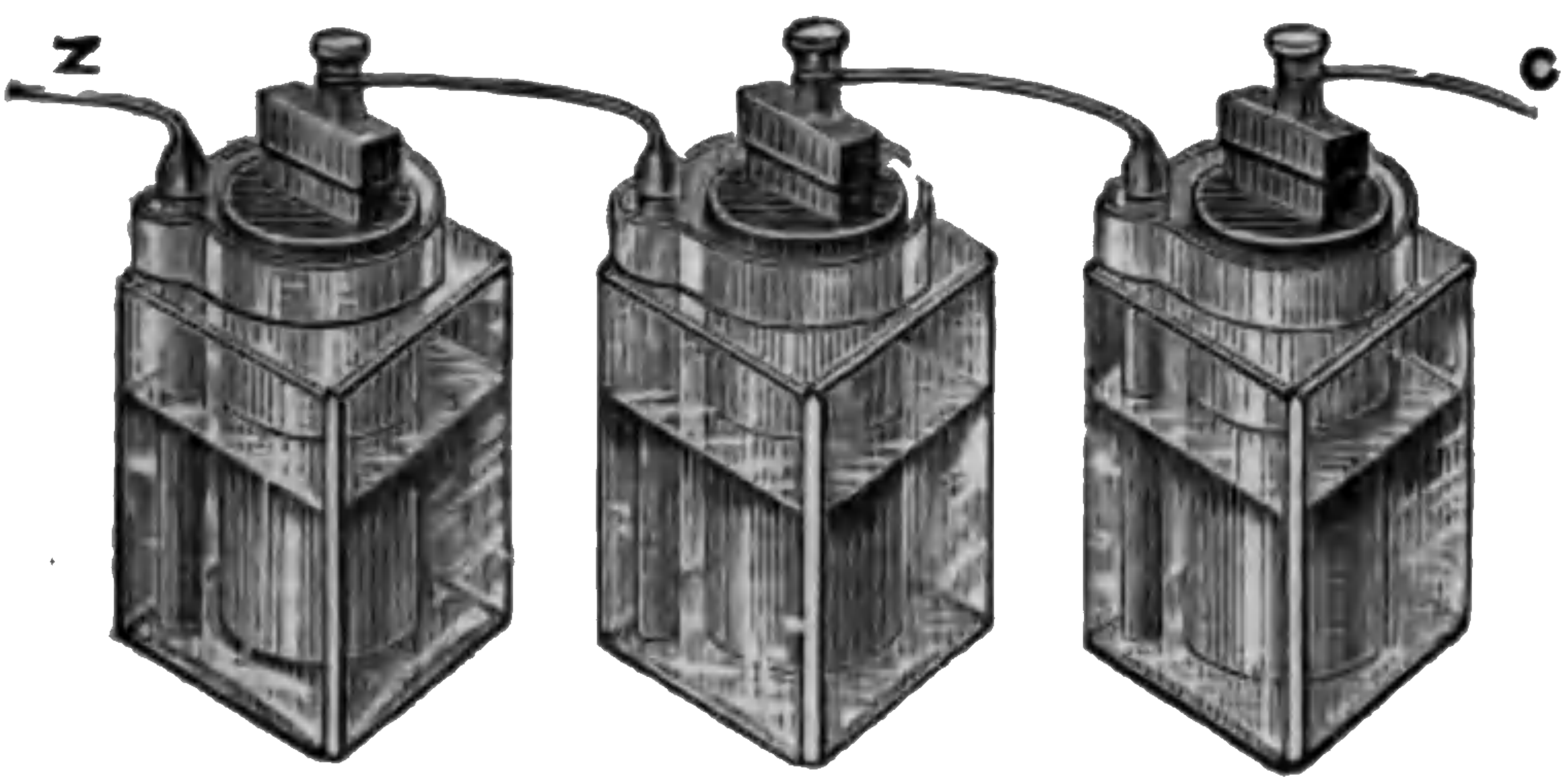


Fig. 104.

yield up oxygen as required. If used to give a continuous current for many minutes together, the power of this cell falls off owing to the accumulation of the hydrogen bubbles; but if left to itself for a time the cell recovers itself, the binoxide gradually destroying the polarization. As the cell is in other respects perfectly constant, and does not require renewing for months or years, it is well adapted for domestic purposes. It has the advantage of not containing corrosive acids. Millions of these cells are in use on "open-circuit" service — that is to say, for those cases in which the current is only required for a few moments at a time, and the circuit usually left open. Three Leclanché cells are shown joined in series, in Fig. 104.

Walker used sulphur in place of oxide of manganese. Niaudet employed bleaching powder (so called chloride of lime) as depolarizer, it being rich in chlorine and oxygen. Common salt may be used instead of salammoniac.

Modifications of the Leclanché cell in which the excitant cannot be spilled are used for portability. The space inside the cell is filled up with a spongy or gelatinous mass, or even with plaster of Paris, in the pores of which the salammoniac solution remains. They are known as *dry cells*.

185. Lalande's Cell.—This cell belongs to Class II., having as depolarizer oxide of copper mechanically attached to a kathode of copper or iron. The anode is zinc, and the exciting liquid is a 30 per cent solution of caustic potash into which the zinc dissolves (forming zincate of potash), whilst metallic copper is reduced in a granular state at the kathode. It has only 0·8 to 0·9 volts of E.M.F., but is capable of yielding a large and constant current.

186. De la Rue's Battery.—De la Rue constructed a constant cell belonging to Class III., in which zinc and silver are the two metals, the zinc being immersed in chloride of zinc, and the silver embedded in a stick of fused chloride of silver. As the zinc dissolves away, metallic silver is deposited upon the kathode, just as the copper is in the Daniell's cell. De la Rue constructed an enormous battery of over 11,000 little cells. The difference of potential between the first zinc and last silver of this battery was over 11.000 volts, yet even so no spark would jump from the + to the − pole until they were brought to within less than a quarter of an inch of one another. With 8040 cells the length of spark was only 0·08 of an inch, or 0·2 cm.

187. Gravity Cells.—Instead of employing a porous cell to keep the two liquids separate, it is possible, where one of the liquids is heavier than the other, to arrange

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189. Statistics of Cells.—The following table gives the electromotive-forces of the various batteries enumerated:—

Name.	Anode.	Excitant.	Depolarizer.	Kathode.	Approximate Volts.
Class I.		(Solution of)			
Volta (Wollaston, etc.) . . .	Zinc	H_2SO_4	none	Copper	1·0 to 0·5
Smee . . .	Zinc	H_2SO_4	none	Platinized Silver	1·0 to 0·5
Law . . .	Zinc	H_2SO_4	none	Carbon	1·0 to 0·5
Class II.					
Poggendorff (Grenet, Fuller, etc.).	Zinc	H_2SO_4	$K_2Cr_2O_7$	Carbon	2·1
Grove . . .	Zinc	H_2SO_4	HNO_3	Platinum	1·9
Bunsen . . .	Zinc	H_2SO_4	HNO_3	Carbon	1·9
Leclanché . .	Zinc	NH_4Cl	MnO_2	Carbon	1·4
Lalande . . .	Zinc	KHO	CuO	Carbon	0·8
Upward . . .	Zinc	$ZnCl_2$	Cl	Carbon	2·0
Fitch . . .	Zinc	NH_4Cl	$KClO_3+NaClO_3$	Carbon	1·1
Papst . . .	Iron	Fe_2Cl_6	Fe_2Cl_6	Carbon	0·4
Obach (dry) . .	Zinc	NH_4Cl in $CaSO_4$	MnO_2	Carbon	1·46
Class III.					
Daniell (Meidinger, Minotto, etc.) .	Zinc	$ZnSO_4$	$CuSO_4$	Copper	1·07
De la Rue . .	Zinc	$ZnCl_2$	AgCl	Silver	1·42
Marié Davy . .	Zinc	$ZnSO_4$	Hg_2SO_4	Carbon	1·4
Clark (Standard) .	Zinc	$ZnSO_4$	Hg_2SO_4	Mercury	1·434
Weston . . .	Cadmium	$CdSO_4$	Hg_2SO_4	Mercury	1·025
Von Helmholtz .	Zinc	$ZnCl_2$	Hg_2Cl_2	Mercury	1·0
Class IV.					
Accumulators. (Planté, Faure, etc.)	Lead	H_2SO_2	PbO_2	Lead	2·1 to 1·85

190. Strength of Current.—The student must not mistake the figures given in the above table for the strength of current which the various batteries will yield; the current depends, as was said in Lesson XIII., on the internal *resistance* of the cells and on that of their

circuit, as well as on their E.M.F. The E.M.F. of a cell is independent of its size, and is determined solely by the materials chosen and their condition. The resistance depends on the size of the cell, the conducting qualities of the liquid, the thickness of the liquid which the current must traverse, etc.

The definition of the **strength** of a current is as follows: *The strength of a current is the quantity of electricity which flows past any point of the circuit in one second.** Suppose that at the end of 10 seconds 25 *coulombs* of electricity to have passed through a circuit, then the average current during that time has been $2\frac{1}{2}$ *coulombs per second*, or $2\frac{1}{2}$ *amperes*. The usual strength of currents used in telegraphing over main lines is only from five to ten thousandths of an *ampere*.

If in t seconds a quantity of electricity Q has flowed through the circuit, then the current C during that time is represented by the equation

$$C = \frac{Q}{t}.$$

This should be compared with Art. 162.

The laws which determine the strength or quantity of a current in a circuit were first enunciated by Dr. G. S. Ohm, who stated them in the following law:—

191. Ohm's Law.—*The current varies directly as the electromotive-force, and inversely as the resistance of the circuit;* or, in other words, anything that makes the

* The terms "strength of current," "intensity of current," are old-fashioned, and mean no more than "current" means—that is to say, the number of *amperes* that are flowing. The terms "strong," "great," and "intense," as applied to currents, mean precisely the same thing. Formerly, before Ohm's Law was properly understood, electricians used to talk about "quantity currents" and "intensity currents," meaning by the former term a current flowing through a circuit in which there is very ***small resistance*** inside the battery or out; and by the latter expression they designated a current due to a ***high electromotive-force***. The terms were convenient, but should be avoided as misleading.

E.M.F. of the cell greater will increase the current, while anything that increases the resistance (either the internal resistance in the cells themselves or the resistance of the external wires of the circuit) will diminish the current.

In symbols this becomes

$$\frac{E}{R} = C,$$

where E is the number of *volts*, R the number of *ohms* of the circuit, and C the number of *amperes* of current.

Example. — To find the current that can be sent through a resistance of 5 *ohms* by an E.M.F. of 20 *volts*. $20 \div 5 = 4$ *amperes*.

(See further concerning Ohm's Law in Lesson XXXIII.) Ohm's Law says nothing about the energy or power conveyed by a current. The *power* of a current is proportional both to the current and to the electromotive-force which drives it (see Art. 435).

192. Resistance and Grouping of Cells. — The internal resistances of the cells we have named differ very greatly, and differ with their size. Roughly speaking, we may say that the resistance in a Daniell's cell is about five times that in a Grove's cell of equal size. The Grove's cell has indeed both a higher E.M.F. and less internal resistance. It would in fact send a current about eight times as strong as the Daniell's cell of equal size through a short stout wire.

We may then increase the strength of a battery in two ways: —

(1) By increasing its E.M.F.

(2) By diminishing its internal resistance.

The electromotive-force of a cell being determined by the materials of which it is made, the only way to increase the total E.M.F. of a battery of given materials is to increase the number of cells joined "in series." It

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already great, as in telegraphing through a long line, it is little use to diminish the internal resistance if this is already much smaller than the resistance of the line wire. It is, on the contrary, advantageous to increase the number of cells in series, though every cell adds a little to the total resistance.

Example.—If the line has a resistance of 1000 *ohms*, and five cells are used each of which has an E.M.F. of 1·1 *volt* and an internal resistance of 3 *ohms*. By Ohm's Law the current will be 5·5 ÷ 1015; or 0·0054 *ampere*. If now eight cells are used, though the total resistance is thereby increased from 1015 to 1040 *ohms*, yet the E.M.F. is increased from 5·5 to 8·8 *volts*, and the current to 0·0085 *ampere*.

The E.M.F. of the single-fluid cells of Volta and Smee is marked in the table as doubtful, for the opposing E.M.F. of polarization sets in almost before the true E.M.F. of the cell can be measured. The different values assigned to other cells are accounted for by the different degrees of concentration of the liquids. Thus in the Daniell's cells used in telegraphy, *water* only is supplied at first in the cells containing the zincs; and the E.M.F. of these is less than if acid or sulphate of zinc were added to the water.

193. **Other Batteries.**—Numerous other forms of battery have been suggested by different electricians. There are three, of theoretical interest only, in which, instead of using two metals in one liquid which attacks them unequally, two liquids are used having unequal chemical action on the metal. In these there is no contact of dissimilar metals. The first of these was invented by the Emperor Napoleon III. Both plates were of copper dipping respectively into solutions of dilute sulphuric acid and of cyanide of potassium, separated by a porous cell. The second of these combinations, due to Wöhler, employs plates of aluminium only, dipping respectively into strong nitric acid and a solution of caustic soda. In

the third, invented by Dr. Fleming, the two liquids do not even touch one another, being joined together by a second metal. In this case the liquids chosen are sodium persulphide and nitric acid, and the two metals copper and lead. A similar battery might be made with copper and zinc, using solutions of ordinary sodium sulphide, and dilute sulphuric acid in alternate cells, a bent zinc plate dipping into the first and second cells, a bent copper plate dipping into second and third, and so on; for the electromotive-force of a copper-sodium-sulphide-zinc combination is in the reverse direction to that of a copper-sulphuric acid-zinc combination.

Upward proposed a chlorine battery, having slabs of zinc immersed in chloride of zinc and kathodes of carbon surrounded by crushed carbon in a porous pot, gaseous chlorine being pumped into the cells, and dissolving into the liquids to act as a depolarizer. It has an E.M.F. of 2 volts.

Bennett described a cheap and most efficient battery, in which old meat-canisters packed with iron filings answer for the positive element, and serve to contain the exciting liquid, a strong solution of caustic soda. Scrap zinc thrown into mercury in a shallow inner cup of porcelain forms the anode.

Marié Davy employed a cell in which the zinc dipped into sulphate of zinc, while a carbon plate dipped into a pasty solution of mercurous sulphate. When the cell is in action mercury is deposited on the surface of the carbon, so that the cell is virtually a zinc-mercury cell. It was largely used for telegraphy in France before the introduction of the Leclanché cell.

Obach's dry cell has an outer cylinder of zinc which serves as a case, lined with plaster of Paris soaked in salammoniac; with a central carbon kathode surrounded with binoxide of manganese mixed with graphite.

The Fitch cell, used in the United States, is a zinc-carbon cell with an excitant composed of salammoniac

solution to which the chlorates of potash and soda have been added.

Papst used an iron-carbon cell with ferric chloride solution as excitant. The iron dissolves and chlorine is at first evolved, but without polarization; the liquid regenerating itself by absorbing moisture from the air. It is very constant but of low E.M.F.

Jablochkoff described a battery in which plates of carbon and iron are placed in fused nitre; the carbon is here the electropositive element, being rapidly consumed in the liquid.

Planté's and Faure's *Secondary Batteries*, and Grove's *Gas Battery*, are described in Arts. 492, 493.

The so-called **Dry Pile** of Zamboni deserves notice. It consists of a number of paper disks, coated with zinc-foil on one side and with binoxide of manganese on the other, piled upon one another, to the number of some thousands, in a glass tube. Its internal resistance is enormous, as the internal conductor is the moisture of the paper, and this is slight; but its electromotive-force is very great, and a good dry pile will yield sparks. Many years may elapse before the zinc is completely oxidized or the manganese exhausted. In the Clarendon Laboratory at Oxford there is a dry pile, the poles of which are two metal bells: between them is hung a small brass ball, which, by oscillating to and fro, slowly discharges the electrification. It has now been continuously ringing the bells for fifty years.

194. Effect of Heat on Cells.—If a cell be warmed it yields a stronger current than when cold. This is chiefly due to the fact that the liquids conduct better when warm, the internal resistance being thereby reduced. A slight change is also observed in the E.M.F. on heating; thus the E.M.F. of a Daniell's cell is about 1½ per cent higher when warmed to the temperature of boiling water, while that of a bichromate battery falls off nearly 2 per cent under similar circumstances. In the

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copper wire, one end of which is joined to one pole of a battery of one or two cells. The other end of the wire is then brought into contact with the other pole of the battery. As soon as the circuit is completed the current flows through the wire and the needle turns briskly aside. If the current be flowing along the wire *above* the needle in the direction from north to south, it will cause the N-seeking end of the needle to turn eastwards; if the current flows from south to north in the wire the N-seek-

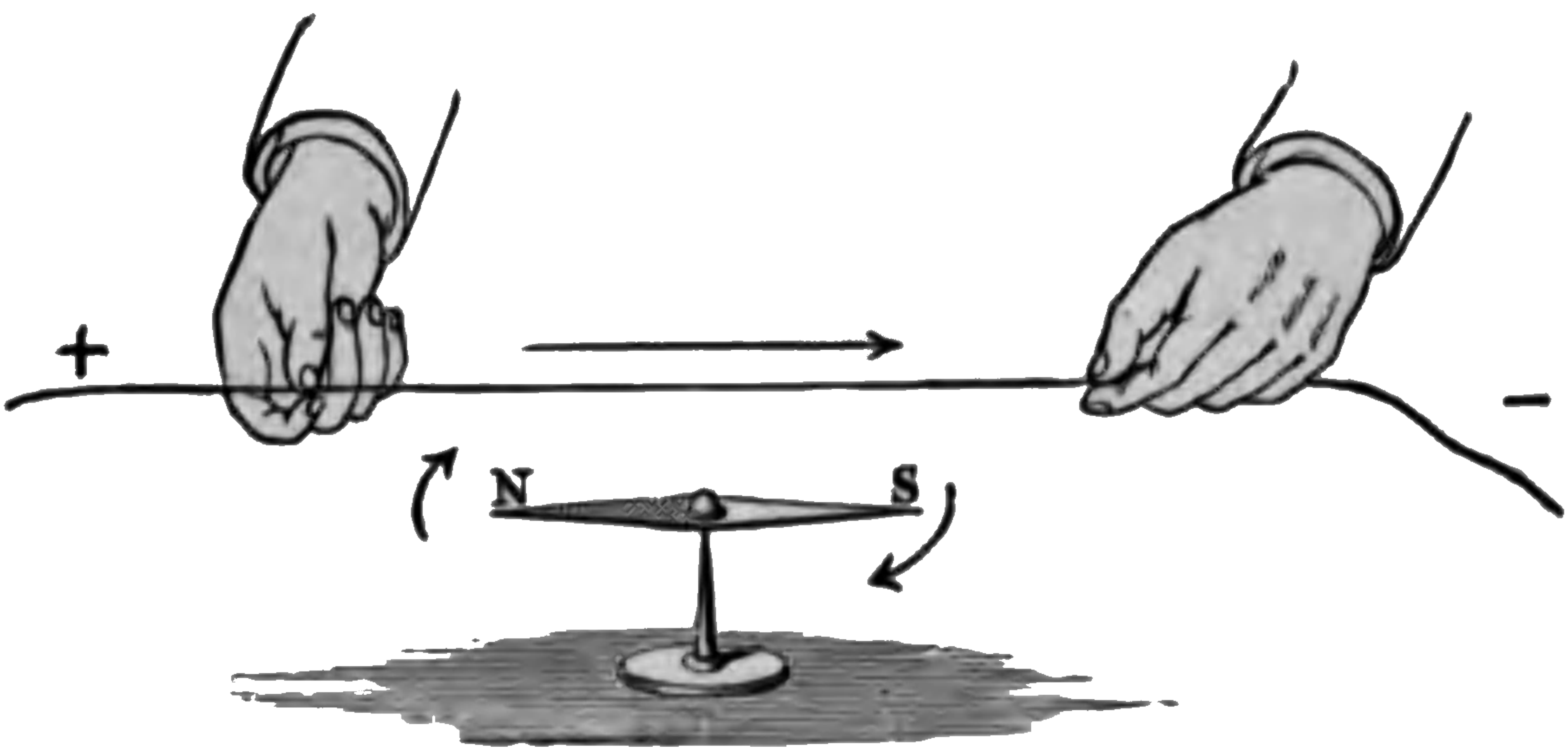


Fig. 107.

ing end of the needle will be deflected westwards. If the wire is, however, *below* the needle, the motions will be reversed, and a current flowing from north to south will cause the N-seeking pole to turn westwards.

197. Ampère's Rule. — To keep these movements in memory, Ampère suggested the following fanciful but useful rule. *Suppose a man swimming in the wire with the current, and that he turns so as to face the needle, then the N-seeking pole of the needle will be deflected towards his* left *hand.* In other words, the deflexion of the N-seeking pole of a magnetic needle, as viewed from the conductor, is towards the left of the current.

For certain particular cases in which a *fixed* magnet pole acts on a *movable* circuit, the following *converse* to

Ampère's Rule will be found convenient. Suppose a man swimming in the wire with the current, and that he turns so as to look along the direction of the lines of force of the pole (*i.e.* as the lines of force run, *from* the pole if it be N-seeking, *towards* the pole if it be S-seeking), then he and the conducting wire with him will be urged *toward his left.*

198. Corkscrew Rule.—More convenient is the following rule suggested by Maxwell. *The direction of the current and that of the resulting magnetic force are related to one another, as are the rotation and the forward travel of an ordinary* (right-handed) *corkscrew.* In Fig. 108, if the circle represents the circulation of current, the arrow gives the direction of the resulting magnetic force. One advantage of this rule is, that it is equally applicable in the other case. If the arrow represents the direction of the current along a straight wire, the circle will represent the direction of the resulting magnetic force around it.

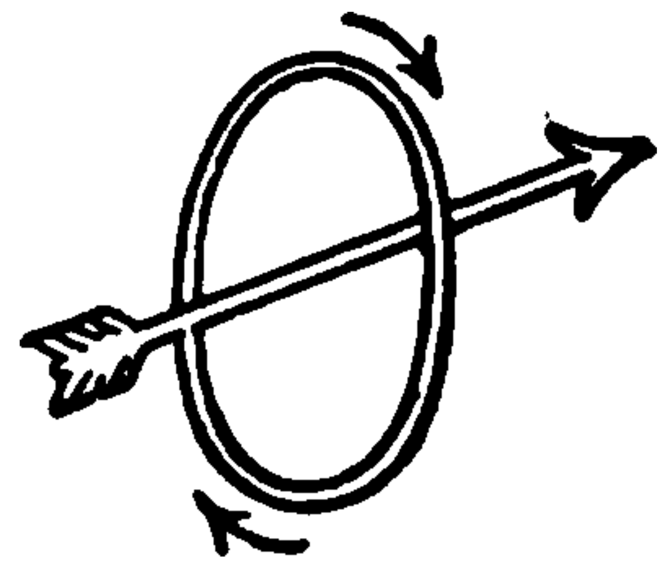


Fig. 108.

199. Galvanoscope. — A little consideration will show that if a current be carried *below* a needle in one direction, and then back in the opposite direction *above* the needle, by bending the wire round, as in Fig. 109, the forces exerted on the needle by both portions of the current will be in the same direction. For let *a* be the N-seeking, and *b* the S-seeking, pole of the suspended needle, then the tendency of the current in the lower part of the wire will be to turn the needle so that *a* comes towards the observer, while *b* retreats; while the current flowing above, which also deflects the N-seeking pole to its left, will equally urge *a* towards the observer, and *b* from him. The needle

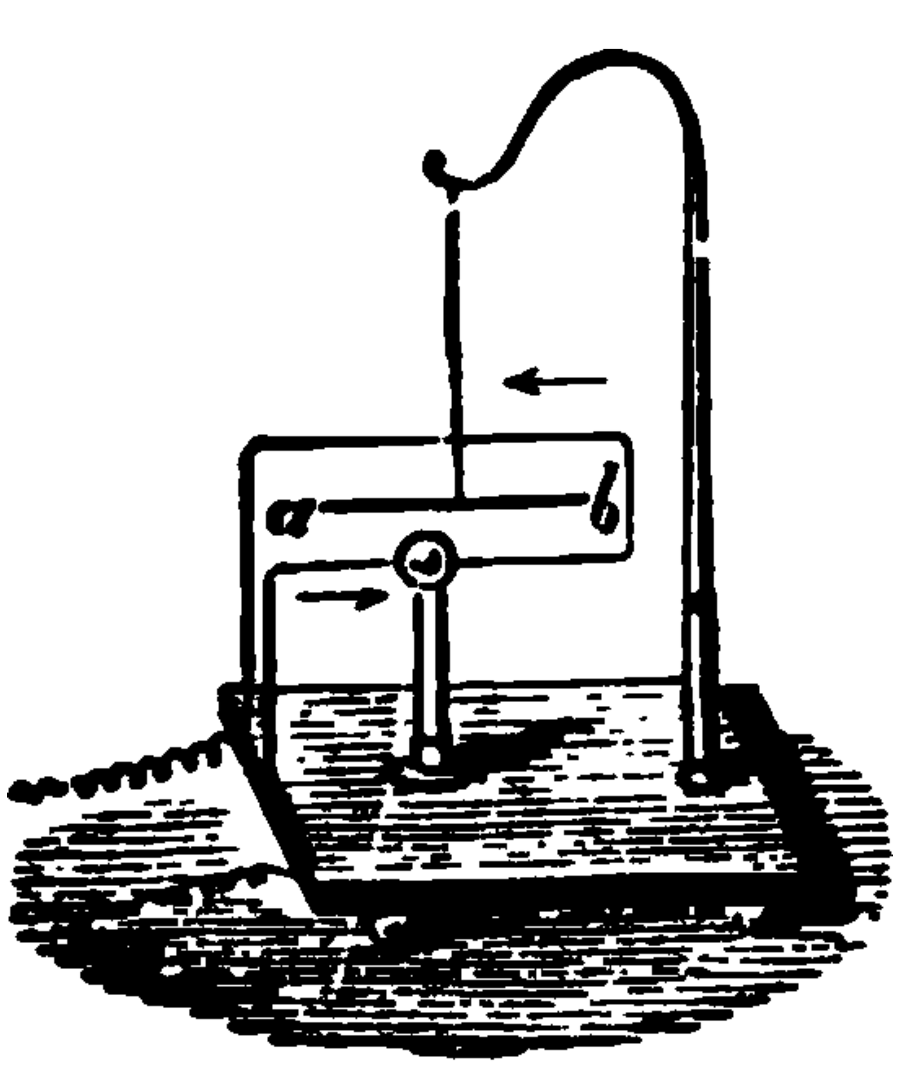


Fig. 109.

will not stand out completely at right angles to the direction of the wire conductor, but will take an oblique position. The directive forces of the earth's magnetism are tending to make the needle point north-and-south. The electric current is acting on the needle, tending to make it set itself west-and-east. The resultant force will be in an oblique direction between these, and will depend upon the relative strength of the two conflicting forces. If the current is very strong the needle will turn widely round; but could only turn completely to a right angle if the current were infinitely strong. If, however, the current is feeble in comparison with the directive magnetic force, the needle will turn very little.

This arrangement will, therefore, serve roughly as a **Galvanoscope** or indicator of currents; for the movement of the needle shows the direction of the current, and indicates whether it is a strong or a weak one. This apparatus is too rough to detect very delicate currents. To obtain a more sensitive instrument there are two possible courses: (i.) increase the effective action of the current by carrying the wire more than once round the needle; (ii.) decrease the opposing directive force of the earth's magnetism by some compensating contrivance.

200. Schweigger's Multiplier. — The first of the above suggestions was carried out by Schweigger, who constructed a *multiplier* of many turns of wire. A suitable frame of wood, brass, or ebonite, is prepared to receive the wire, which must be "insulated," or covered with silk, or cotton, or guttapercha, to prevent the separate turns of the coil from coming into contact with each other. Within this frame, which may be circular, elliptical, or more usually rectangular, as in Fig. 110, the needle is suspended, the frame being placed so that the wires lie in the magnetic meridian. The greater the number of turns the more powerful will be the magnetic

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(*b*) [*Nobili's Method*]. By using an *astatic pair* of magnetic needles. If two magnetized needles of equal strength and size are bound together by a light wire of brass, or aluminium, in reversed positions, as shown in Fig. 111, the force urging one to set itself in the magnetic meridian is exactly counterbalanced by the force that acts on the other. Consequently this pair of needles will remain in any position in which it is set, and is independent of the earth's magnetism. Such a combination is known as an **astatic pair**. It is, however, difficult in practice to obtain a perfectly astatic pair, since it is not easy to magnetize two needles exactly to equal strength, nor is it easy to fix them perfectly parallel to one another. Such an astatic pair is, however, readily deflected by a current flowing in a wire coiled around one of the needles; for, as shown in Fig. 112, the current which flows above one needle and below the other will urge both in the same direction, because they are already in reversed positions. It is even possible to go further, and to carry the wire round both needles, winding the coil around the upper in the opposite sense to that in which the coil is wound round the lower needle. Several other astatic combinations are possible. For example, two needles may be set vertically, with similar poles upward, at the ends of a pivoted horizontal strip of wood or brass.

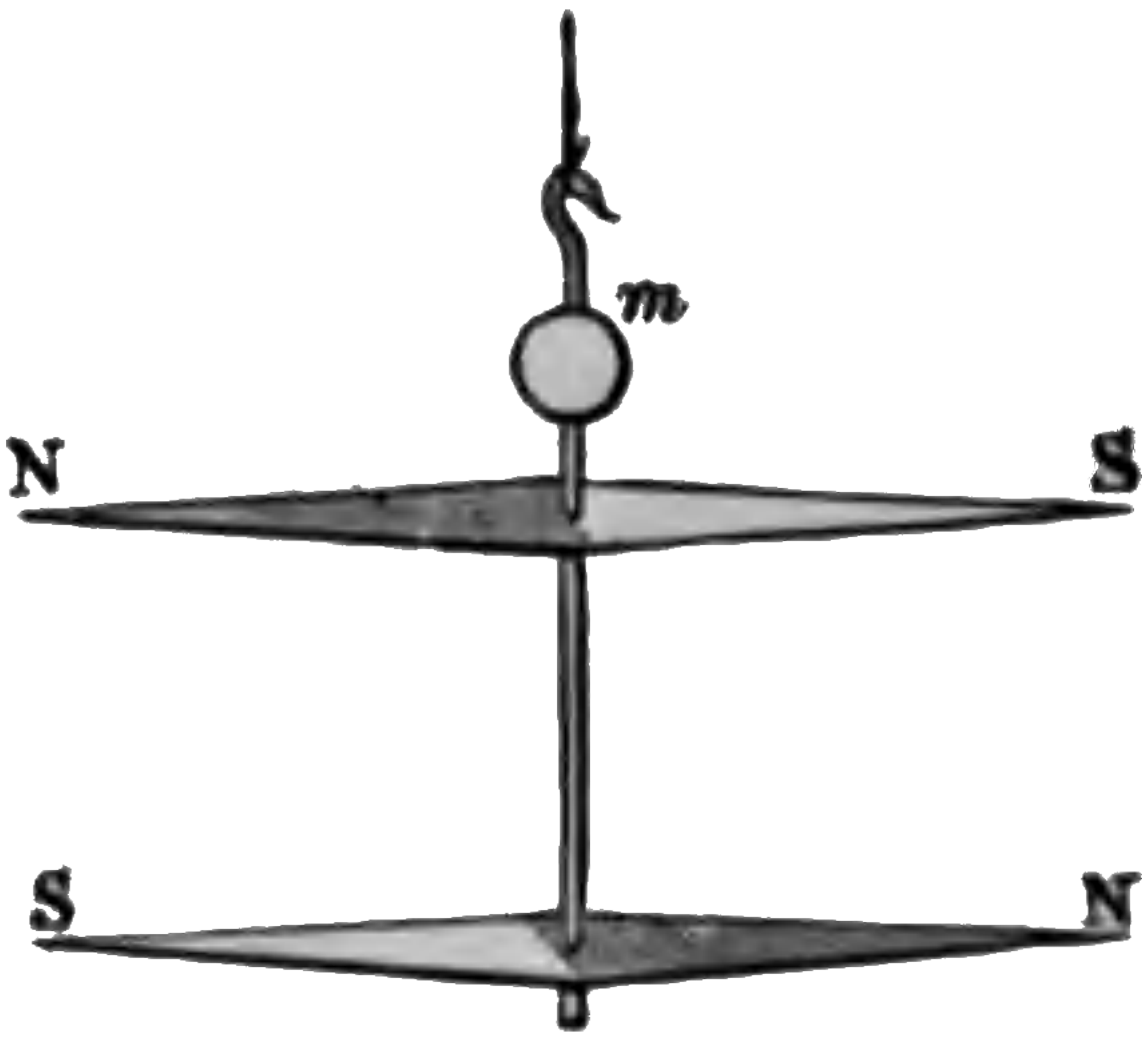


Fig. 111.

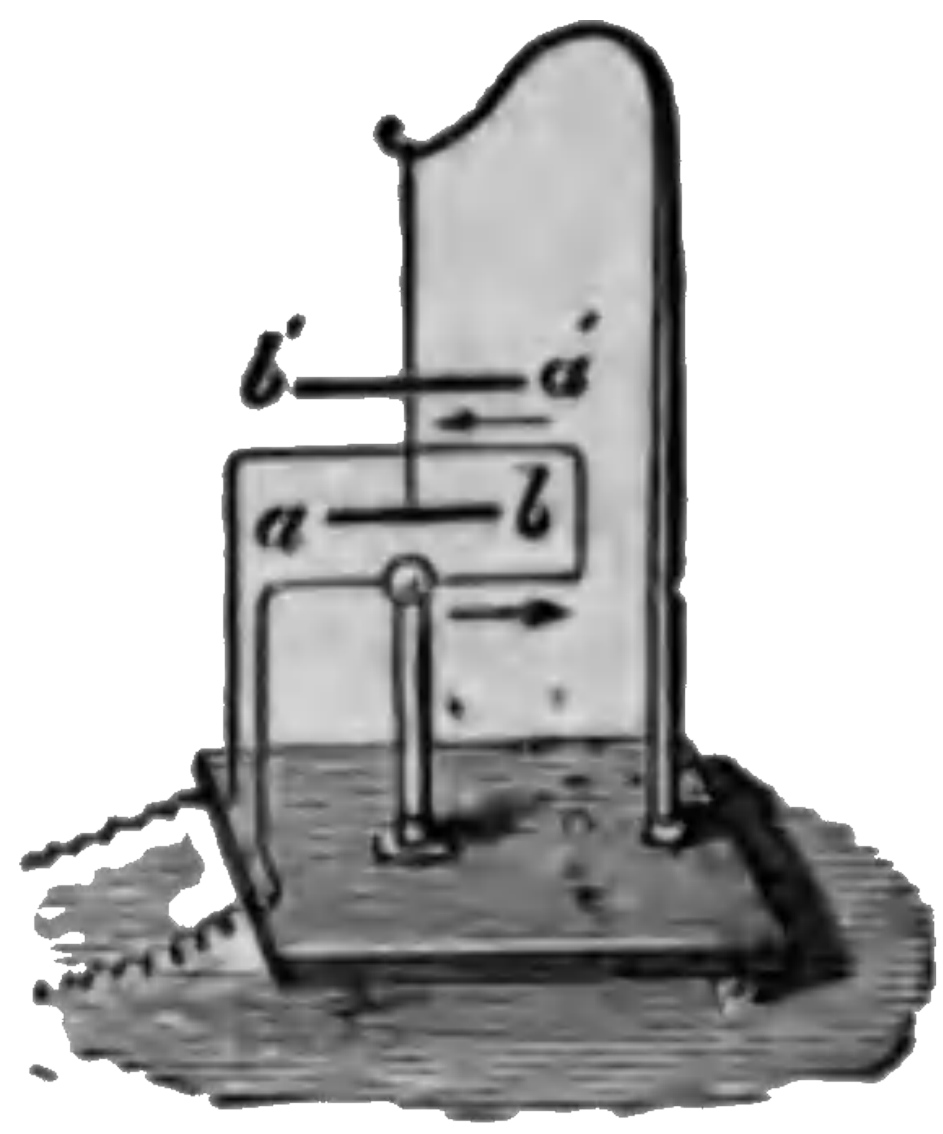


Fig. 112.

Nobili applied the astatic arrangement of needles to the multiplying coils of Schweigger, and thus constructed

a very sensitive instrument, the *Astatic Galvanometer*, shown in Fig. 119. The special forms of galvanometer adapted for the measurement of currents are described in the next lesson.

202. Magnetic Field due to Current: Magnetic Whirls. — Arago found that if a current be passed through a piece of copper wire it becomes capable of attracting iron filings to it so long as the current flows. These filings set themselves at right angles to the wire, and cling around it, but drop off when the circuit is broken. There is, then, a magnetic "field," around the wire which carries the current; and it is important to know how the lines of force are distributed in this field.

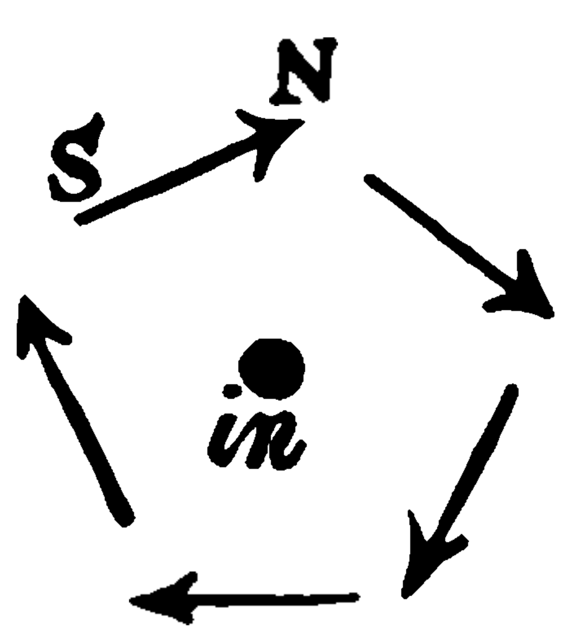


Fig. 118.

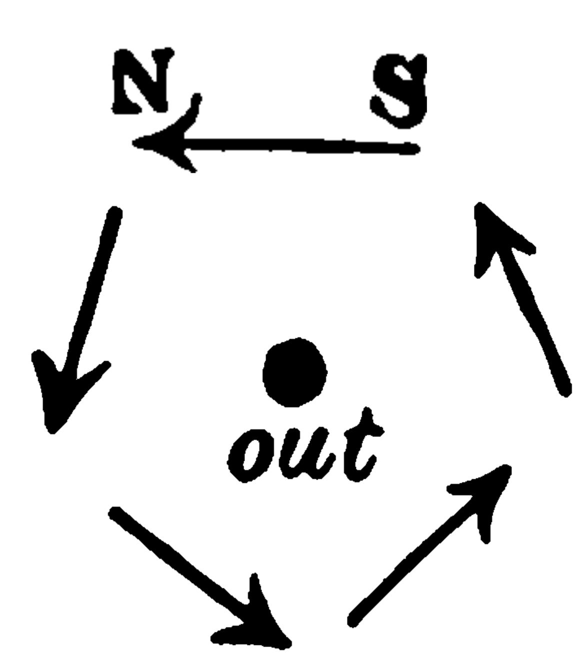


Fig. 114.

Let the central spot in Fig. 113 represent an imaginary cross-section of the wire, and let us suppose the current to be flowing in through the paper at that point. Then by Ampère's rule a magnet needle placed below will tend to set itself in the position shown, with its N pole pointing to the left.* The current will urge a needle above the wire into the reverse position. A needle on the right of the current will set itself at right angles to the current (*i.e.* in the plane of the paper), and with its N pole pointing *down*, while the N pole of a needle on the left would be urged *up*. In fact the tendency would be to urge the N pole round the conductor in the same

* If the student has any difficulty in applying Ampère's rule to this case and the others which succeed, he should carefully follow out the following mental operation. Consider the spot marked "*in*" as a hole in the ground into which the current is flowing, and into which he dives head-foremost. While in the hole he must turn round so as to face each of the magnets in succession, and remember that in each case the N-seeking pole will be urged to *his* left. In diagram 84 he must conceive himself as coming up *out* of the hole in the ground where the current is flowing out.

way as the hands of a watch move; while the S pole would be urged in the opposite cyclic direction to that of the hands of a watch. If the current is reversed, and is regarded as flowing towards the reader, *i.e.* coming up *out* of the plane of the paper, as in the diagram of Fig. 114, then the motions would be just in the reverse sense. It would seem from this as if a N-seeking pole of a magnet ought to revolve continuously round and round a current; but as we cannot obtain a magnet with one pole only, and as the S-seeking pole is urged in an opposite direction, all that occurs is that the needle sets itself as a tangent to a circular curve surrounding the conductor. The field surrounding the conductor consists in fact of a sort of enveloping magnetic whirl all along it, the whirl being strong near the wire and weaker farther away. This is what Oersted meant when he described the electric current as acting "in a revolving manner" upon the magnetic needle. The field of force, with its circular lines surrounding a current flowing in a straight conductor, can be examined experimentally with iron filings in the following way: A card is placed horizontally and a stout copper wire is passed vertically through a hole in it (Fig. 115). Iron filings are sifted over the card (as described in Art. 119), and a strong current from three or four large cells is passed through the wire. On tapping the card gently the filings near the wire set themselves in concentric circles round it. It is because of this surrounding field that two conductors can apparently act on one another at a distance. If both currents are flowing in the same direction, their magnetic fields tend to merge, and the resulting stress in the medium tends to drag them together with an apparent attraction. If the currents are flowing in opposite

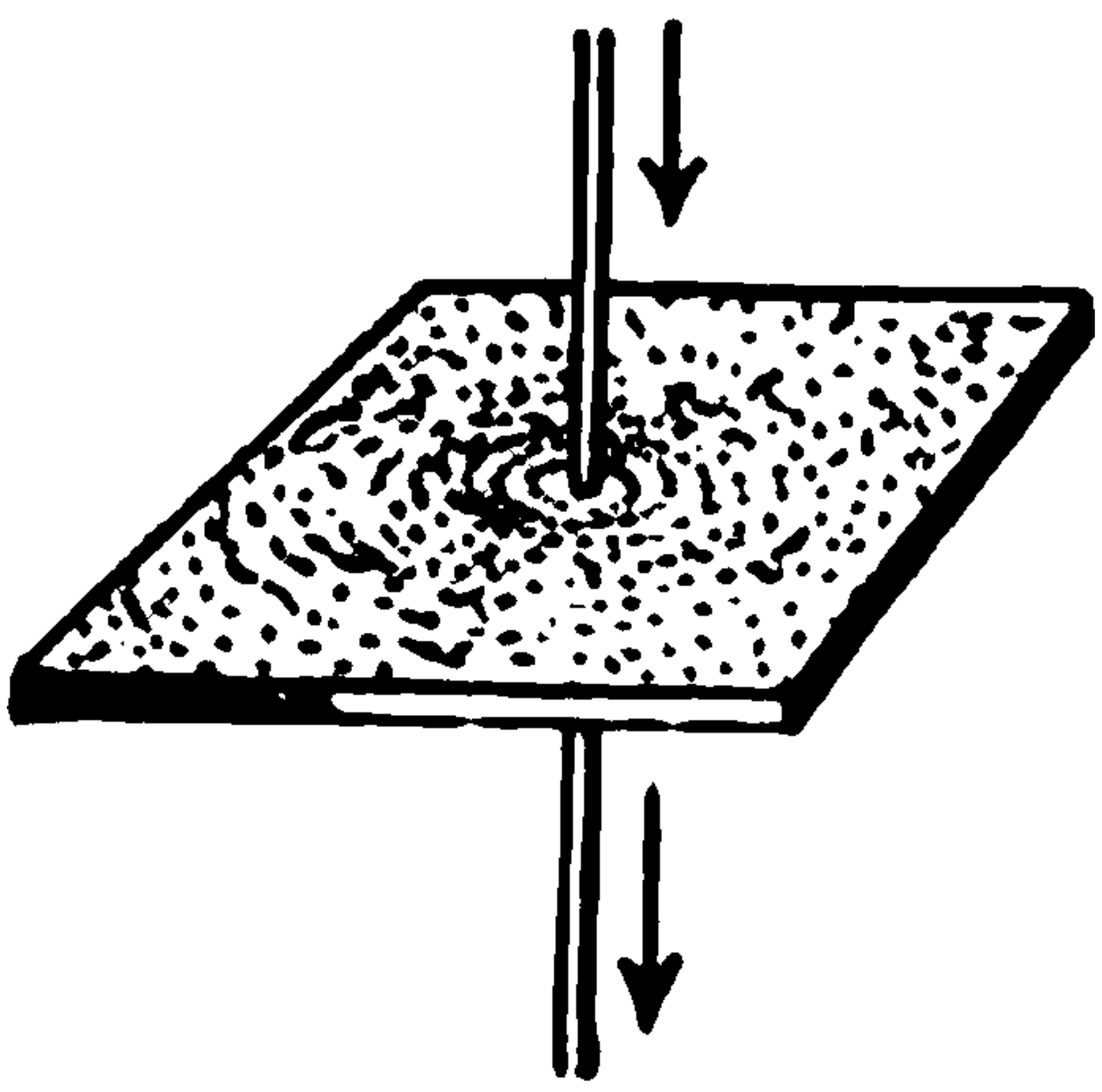


Fig. 115.

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the loop, as viewed from above, in the same direction as the hands of a clock move round; an imaginary man swimming round the circuit and always facing towards the centre would have his left side down. By Ampère's rule, then, a N pole would be urged downwards through the loop, while a S pole would be urged upwards. In fact the space enclosed by the loop of the circuit behaves like a *magnetic shell* (see Art. 118), having its upper face of S-seeking magnetism, and its lower face of N-seeking magnetism. It can be shown in every case that *a closed voltaic circuit is equivalent to a magnetic shell whose edges coincide in position with the circuit*, the shell being of such a strength that the number of its lines of force is the same as that of the lines of force due to the current in the circuit. The circuit acts on a magnet attracting or repelling it, and being attracted or repelled by it, just exactly as its equivalent magnetic shell would do. Also, the circuit itself, when placed in a magnetic field, experiences the same force as its equivalent magnetic shell would do.

204. Maxwell's Rule. — Professor Clerk Maxwell, who developed this method of treating the subject, has given the following elegant rule for determining the mutual action of a circuit and a magnet placed near it. *Every portion of the circuit is acted upon by a force urging it in such a direction as to make it enclose within its embrace the greatest possible number of lines of force.* If the circuit is fixed and the magnet movable, then the force acting on the magnet will also be such as to tend to make the number of lines of force that pass through the circuit a maximum (see also Art. 349).

This is but one case of the still more general law governing every part of every electromagnetic system, viz.: *Every electromagnetic system tends so to change the configuration of its parts as to make the flux of magnetic lines through the exciting circuit a maximum.* (Art. 379.)

205. De la Rive's Floating Battery. — The preced-

ing remarks may be illustrated experimentally by the aid of a little floating battery. A plate of zinc and one of copper (see Fig. 117) are fixed side by side in a large cock, and connected above by a coil of several windings of covered copper wire. This is floated upon a dish containing dilute sulphuric acid. If one pole of a bar magnet be held towards the ring it will be attracted or repelled according to the pole employed. The floating circuit will so move as to make the flux of magnetic lines through the

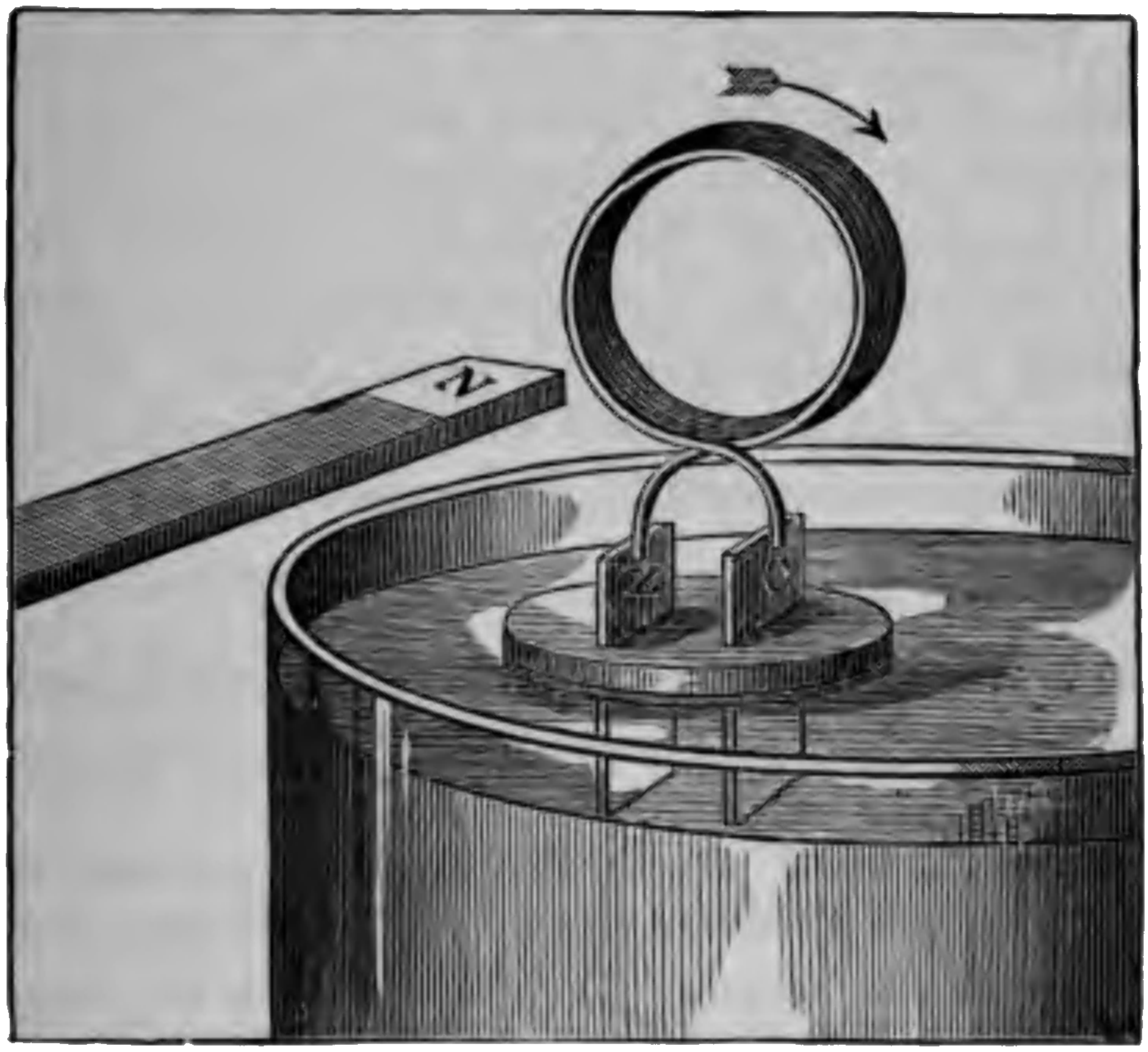


Fig. 117.

coil a maximum. If the S pole of the magnet be presented to that face of the ring which acts as a S-seeking pole (viz. that face round which the current is flowing in a clockwise direction), it will repel it. If the pole be thrust right into the ring, and then held still, the battery will be strongly repelled, will draw itself off, float away, turn round so as to present toward the S pole of the magnet its N-seeking face, will then be attracted up, and will thread itself on to the magnet up to the middle, in

which position as many magnetic lines of force as possible cross the area of the ring.

It can be shown also that two circuits traversed by currents attract and repel one another just as two magnetic shells would do.

It will be explained in Lesson XXXI. on Electromagnets how a piece of iron or steel can be magnetized by causing a current to flow in a spiral wire round it.

206. Strength of the Current in Magnetic Measure. — When a current thus acts on a magnet pole near it, the force f which it exerts will be proportional to the strength C of the current, and proportional also to the strength m of the magnet pole, and to the length l of the wire employed: the force exerted between each element of the circuit and the pole will also vary inversely as the square of the distance r between them. If the wire is looped into a circular coil with the magnet pole at the centre, so that each portion of the circuit is approximately at the same distance from the pole, $f = \frac{Clm}{r^2}$ dynes. Suppose the wire looped up into a circle round the magnet pole, then $l = 2\pi r$, and $f = \frac{2\pi C}{r} m$ dynes. Suppose also that the circle is of *one* centimetre radius, and that the magnet pole is of strength of *one* unit (see Art. 352), then the force exerted by the current of strength C will be $\frac{2\pi C}{1} \times 1$, or $2\pi C$ dynes. In order, therefore, that a current of strength C should exert a force of C dynes on the unit pole, one must consider the current as travelling round only $\frac{1}{2\pi}$ part of the circle, or round a portion of the circumference equal in length to the radius.

207. Unit of Current. — A current is said to have a strength of one "absolute" unit when it is such that if one centimetre length of the circuit is bent into an arc of one centimetre radius, the current in it exerts a force of

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The simple arrangement described in Art. 199 was termed a "Galvanoscope," or current *indicator*, but it could not rightly be termed a "galvanometer" * or current *measurer*, because its indications were only qualitative, not quantitative. The indications of the needle did not afford accurate knowledge as to the exact strength of current flowing through the instrument. A good galvanometer must fulfil the essential condition that its readings shall really *measure* the strength of the current in some certain way. It should also be sufficiently sensitive for the currents that are to be measured to affect it. The galvanometer adapted for measuring very small currents (say a current of only one or two millionth parts of an *ampere*) will not be suitable for measuring very strong currents, such as are used in electric lighting or electroplating. Large currents need thick wires; and a coil of few turns will suffice. If very small currents are to turn the needle they must circulate hundreds or thousands of times around it, and therefore a coil of many turns is appropriate, and the wire may be a very fine one. Moreover, if the current to be measured has already passed through a circuit of great resistance (as, for example, some miles of telegraph wire), a galvanometer whose coil is a short one, consisting only of a few turns of wire, will be of no use, and a long-coil galvanometer must be employed with many hundreds or even thousands of turns of insulated wire round the needle. The reason of this is explained hereafter (Art. 408). Hence it will be seen that different styles of instrument are needed for different kinds of works; but of all it is required that they should afford quantitative measurements, that they should be sufficiently sensitive for the current that is to be measured, and carry that current without overheating.

* The terms *Rheoscope* and *Rheometer* are still occasionally applied to these instruments. A current interrupter is sometimes called a *Rheotome*, and the Commutator or Current Reverser, shown in Fig. 186, is in some books called a *Rheotrope*; but these terms are dropping out of use.

209. Methods of Control. — In all instruments, whether the moving part be a magnet or a coil, some controlling force is needful, otherwise the very smallest current would turn the index completely about. If small currents are to produce a small deflexion, and larger currents a larger, there must be forces tending to control. Several means of control may be used. These are: —

(*a*) *Earth's Magnetic Force.* — When the needle is hung on pivot or fibre, the earth's magnetic force tries to bring it back into the magnetic meridian. This is the commonest method in galvanometers with moving needles.

(*b*) *Torsion of Wire.* — Moving part in turning twists the suspending wire, which then tries to untwist, with a force which increases as the angle of deflexion. This method is commonest in galvanometers with suspended coils.

(*c*) *Gravity.* — If needle is pivoted on trunnions to move in vertical plane, it may be weighted at one end.

(*d*) *Permanent Magnet Control.* — To render a needle instrument independent of position, it may be arranged with a powerful external steel magnet to bring the needle back to zero.

(*e*) *Bifilar Suspension.* — A needle or coil hung by two parallel threads tends by gravity to return to its initial position.

To make an instrument very sensitive the control must be weakened as much as possible.

210. Methods of Observation. — There are following methods of using galvanometers in making observations: —

(i.) *Deflexion Method.* — The angle through which the moving part (whether needle or coil) is deflected is read off on a scale, by pointer or reflected beam of light, when the moving part has come to rest. This is the commonest method.

(ii.) *Torsion Method.* — The moving part is suspended by a wire from a torsion head, which is turned

round until the index is brought back to zero; the controlling force then balancing the deflecting force. This very accurate method, due to Ohm, is used in Siemens' electrodynamometer (Art. 394).

(iii.) *First Swing Method.* — Instead of waiting for moving part to come to rest the *first swing* may be observed. This method which is the only one practicable for sudden discharges, or for transient currents, is called the *ballistic* method (see Art. 218). If the moving part is not damped in its motion the first swing on turning on a battery current is exactly twice the angle at which the deflexion settles down.

(iv.) *Oscillation Method.* — Instead of observing deflexion, the time of oscillation of the needle may be observed, the coil being in this method set at right angles to the magnetic meridian. Allowance must be made, as in Art. 133, for the earth's magnetism.

(v.) *Cumulative Method.* — For very minute currents a method is sometimes adopted to get up a measurable swing by reversing the current (by hand) as the needle swings through zero. Sometimes a rotating commutator of special construction is employed to produce, and accumulate, the successive impulses.

(vi.) *Null Methods.* — In many cases combinations are used (Wheatstone's "Bridge," "Differential Galvanometers," etc.) of such a kind that when the conditions of electrical equilibrium are attained no current will flow through the galvanometer in the circuit. Such methods, which are generally exceedingly accurate, are known as *null methods.* For such methods sensitive galvanometers are applicable, but the graduation of their scale is unimportant.

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the other part of the force is uselessly pulling or pushing the needle along its length. It is, however, possible to *calibrate* the galvanometer — that is, to ascertain by special measurements, or by comparison with a standard instrument, to what strengths of current particular amounts of deflexion correspond. Thus, suppose it once known that a deflexion of 32° on a particular galvanometer is produced by a current of $\frac{1}{10}$ of an ampere, then a current of that strength will *always* produce on that instrument the same deflexion, unless from any accident the controlling force has been altered.

212. The Tangent Galvanometer. — It is not — for the reasons mentioned above — possible to construct a

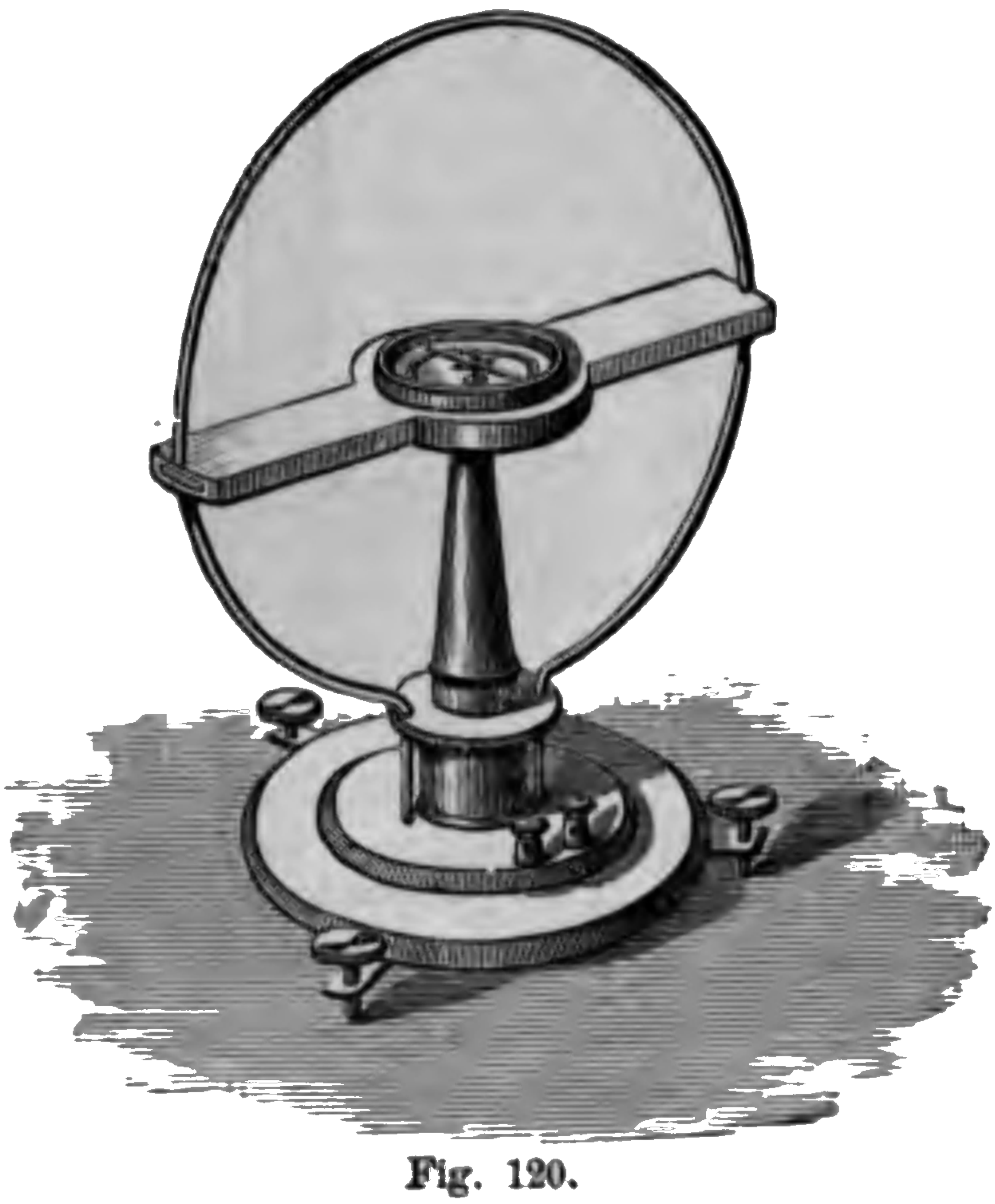


Fig. 120.

galvanometer in which the *angle* (as measured in degrees of arc) through which the needle is deflected is proportional throughout its whole range to the strength of the current. But it is possible to construct a very simple galvanometer

in which the *tangent** of the angle of deflexion shall be accurately proportional to the strength of the current. The essential feature of all tangent galvanometers is that while the coil is a large open ring the needle is relatively very small. Fig. 120 shows a form of **Tangent Galvanometer** suitable for large currents. The coil of this instrument consists of a simple circle of stout copper wire from 10 to 15 inches in diameter. Other tangent galvanometers have many turns of fine wire wound upon a large open ring. At the centre is delicately suspended a magnetized steel needle not exceeding 1 inch in length, and usually furnished with a light index of aluminium. The instrument is adjusted by setting the coil in the magnetic meridian, the small needle lying then in the plane of the coil.

The "field" due to a current passing round the circle is very uniform at and near the centre, and the lines of force are there truly normal to the plane of the coil. This is not true of other parts of the space inside the ring, the force being neither uniform nor normal in direction, except centrally *in* the plane of the coil and along the axis. The needle being small, its poles are never far from the centre, and hence never protrude into the regions where the field is irregular.† Whatever magnetic force the current in the coil can exert on the needle is exerted normally to the plane of the ring, and therefore at right angles to the magnetic meridian. As the two forces — that due to the current and that due to the controlling magnetism of the earth — act squarely to one

* See note on Ways of Reckoning Angles, p. 138.

† In order to ensure uniformity of field, Gaugain proposed to hang the needle at a point on the axis of the coil distant from its centre by a distance equal to half the radius of the coils. Helmholtz's arrangement of *two* parallel coils, symmetrically set on either side of the needle, is better; and a *three coil* galvanometer, having the central coil larger than the others, so that all three may lie in the surface of a sphere having the small needle at its centre, is the best arrangement of all for ensuring that the field at the centre is uniform.

another, the action of the current will not be measured by equal degrees marked out around a circle, but will be measured by equal divisions along a tangent line, as shown below. Now, it was proved in Art. 137 that the magnetic force which, acting at right angles to the meridian, produces on a magnetic needle the deflexion δ is equal to the horizontal force of the earth's magnetism at that place multiplied by the *tangent* of the angle of deflexion. Hence a current flowing in the coil will turn the needle aside through an angle such that *the tangent of the angle of deflexion is proportional to the strength of the current.*

Example.—Suppose a certain battery gave a deflexion of 15° on a tangent galvanometer, and another battery yielding a stronger current gave a deflexion of 30°. The strengths currents are *not* in the proportion of 15 : 30, but in the proportion of tan 15° to tan 30°. These values must be obtained from a table of natural tangents like that given in Appendix A, from which it will be seen that the ratio between the strengths of the currents is ·268 : ·577, or about 10 : 22.

Or, more generally, if current C produces deflexion δ, and current C' deflexion δ', then

$$C : C = \tan\delta : \tan\delta'.$$

To obviate reference to a table of figures, the circular scale of the instrument is sometimes graduated into

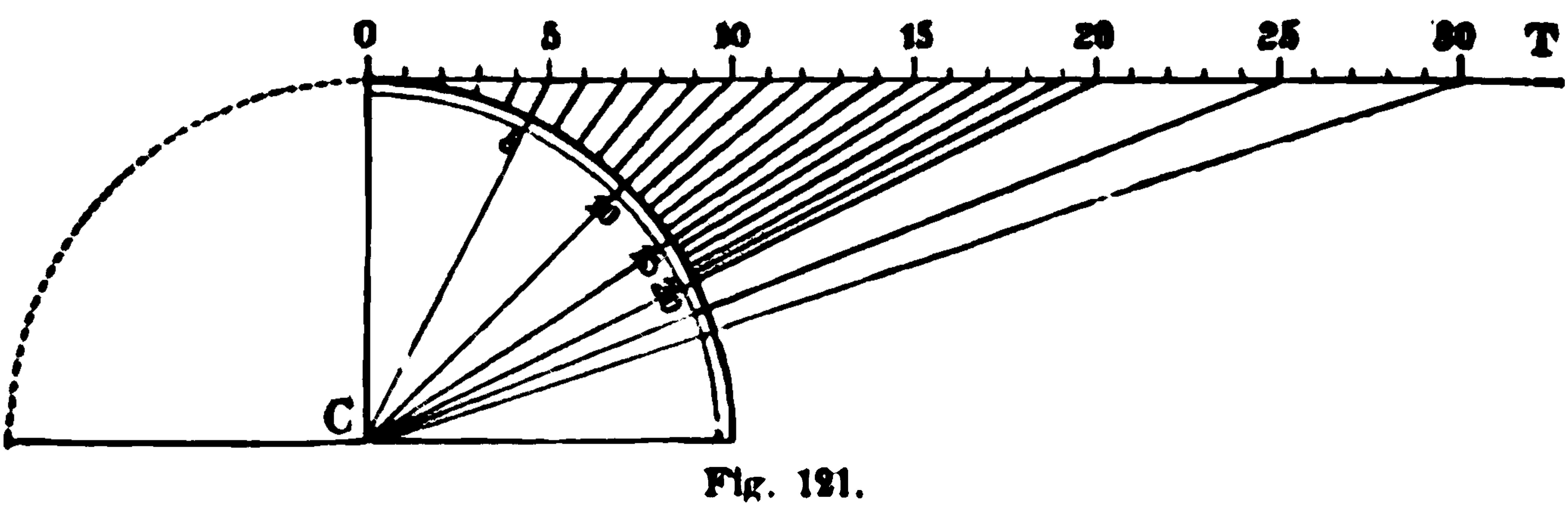


Fig. 121.

tangent values instead of being divided into equal degrees of arc. Let a tangent OT be drawn to the

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hence $$C = \frac{r}{2\pi} \cdot H \cdot \tan \delta.$$

The quantity $2\pi/r$, or $2\pi n/r$ if the coil has n turns, is sometimes called the "constant" or the "principal constant" of the galvanometer and denoted by the symbol G. Hence the value of the current in absolute (electromagnetic) units* will be expressed as

$$C = \frac{H}{G} \cdot \tan \delta.$$

The constant G represents the strength of field produced at the centre of the coil by unit current.

214. Sine Galvanometer. — The disadvantage of the tangent galvanometer just described is that it is not very sensitive, because the coil is necessarily very large as compared with the needle, and therefore far away from it. A galvanometer with a smaller coil or a larger needle could not be used as a tangent galvanometer, though it would be more sensitive. *Any* sensitive galvanometer in which the needle is directed by the earth's magnetism can, however, be used as a **Sine Galvanometer**, provided the frame on which the coils are wound is capable of being turned round a central axis. When the instrument is so constructed, the following method of measuring currents is adopted. The coils are first set parallel to the needle (*i.e.* in the magnetic meridian); the current is then sent through it, producing a deflexion; the coil itself is rotated round in the same sense, and, if turned round through a wide enough angle, will overtake the needle, which will once more lie parallel to the coil. In this position two forces are acting on the needle: the directive force of the earth's magnetism acting along the magnetic meridian, and the force due to the current passing in the coil, which tends to thrust the poles of the needle out at right angles;

* The student will remember (Arts. 207 and 354) that the practical unit of current which we call "one *ampere*" is only $\frac{1}{10}$ of one "absolute" unit of the centimetre-gramme-second system.

in fact there is a "couple" which exactly balances the "couple" due to terrestrial magnetism. Now it was shown in the Lesson on the Laws of Magnetic Force (Art. 136) that when a needle is deflected the "moment" of the couple is proportional to the sine of the angle of deflexion. Hence in the sine galvanometer, when the coil has been turned round so that the needle once more lies along it, *the strength of the current in the coil is proportional to the sine of the angle through which the coil has been turned.**

215. The Mirror Galvanometer.—When a galvanometer of great delicacy is needed, the moving parts must be made very light and small. To watch the movements of a very small needle an *index* of some kind must be used; indeed, in the tangent galvanometer it is usual to fasten to the short stout needle a delicate stiff pointer of aluminium. A far better method is to fasten to the needle a very light mirror of silvered glass, by means of which a beam of light can be reflected on to a scale, so that every slightest motion of the needle is magnified and made apparent. The *mirror galvanometers* devised by Sir W. Thomson (Lord Kelvin) for signalling through submarine cables, are admirable examples of this class of instrument. In Fig. 122 the general arrangements of this instrument are shown. The body of the galvanometer, consisting of a bobbin on which is wound the coil, is sup-

* Again the student who desires to compare the strength of two currents will require the help of a table of natural sines, like that given in Appendix A. Suppose that with current C the coils had to be turned through an angle of θ degrees; and that with a different current C′ the coils had to be turned through θ' degrees, then

$$C : C' = \sin\theta : \sin\theta'.$$

It is of course assumed that the instrument is provided with a scale of degrees on which to read off the angle through which the coils have been turned. It is possible here also, for rough purposes, to graduate the circle not in degrees of arc, but in portions corresponding to equal additional values of the sine. The student should try this way of dividing a circle after reading the note On Ways of Reckoning Angles, p. 188.

ported on three screw feet by which it can be adjusted. The magnet consists of one or more small pieces of steel watch-spring attached to the back of a light concave silvered glass mirror about as large as a threepenny piece, weighing altogether only two or three grains. This mirror is hung by a single fibre of cocoon silk within the coil, and a curved magnet, which serves to counteract the

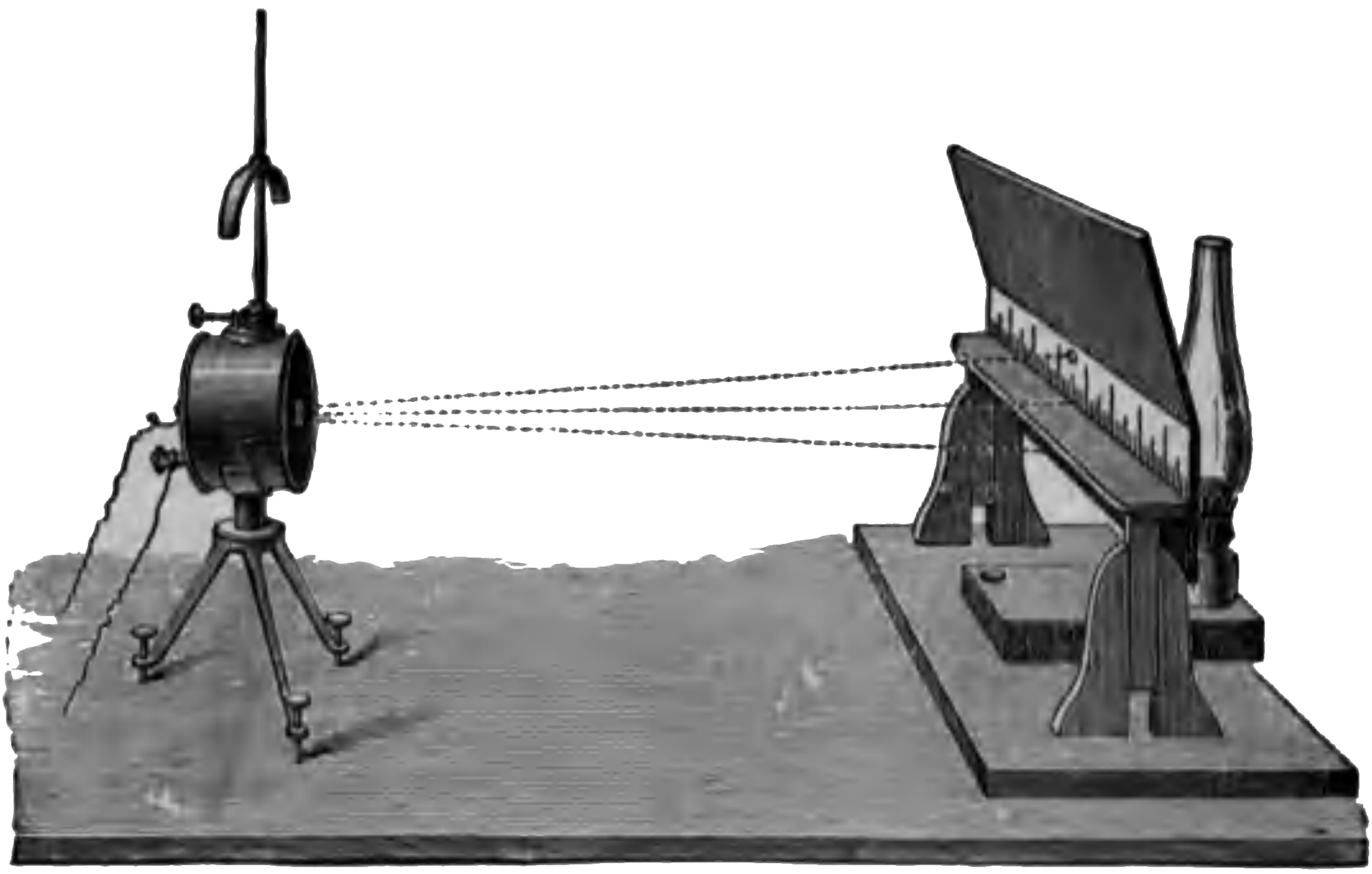


Fig. 122.

magnetism of the earth, or to direct the needle, is carried upon a vertical support above. Another view of the suspended mirror and magnets is shown in Fig. 123. Opposite the galvanometer is placed the scale. A beam of light from a paraffin lamp passes through a narrow aperture under the scale and falls on the mirror, which reflects it back on to the scale. The mirror is slightly concave, and gives a well-defined spot of light if the scale is adjusted to suit the focus of the mirror. The adjusting magnet enables the operator to bring the reflected spot of

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"Siphon Recorder." The best known is that of D'Arsonval depicted in Fig. 125. Between the poles of a compound permanent steel magnet of U-shape is suspended by very thin hard-drawn silver wires an open coil of very fine wire wound on a light rectangular frame. The current is led to and from the coil by the suspending wires. Within the suspended coil is a cylinder of soft iron, supported from behind, to concentrate the magnetic field. The vertical parts of the coil then hang freely in the two narrow gaps where the magnetic field is very intense. The force tending to turn the coil is proportional to the current, to the number of windings, and to the intensity of the magnetic field, so that by making the magnet very powerful the instrument becomes very sensitive. The elasticity of the suspending wires controls the position of the coil and tends to bring it back to its initial position. These galvanometers are independent of the earth's magnetic field, and are not affected by magnets in their neighbourhood, so that they can be used in many places where other galvanometers could not. They are also remarkably dead-beat. Some are provided with a pointer and a horizontal dial; others more usually have a mirror attached to the coil to reflect a spot of light.

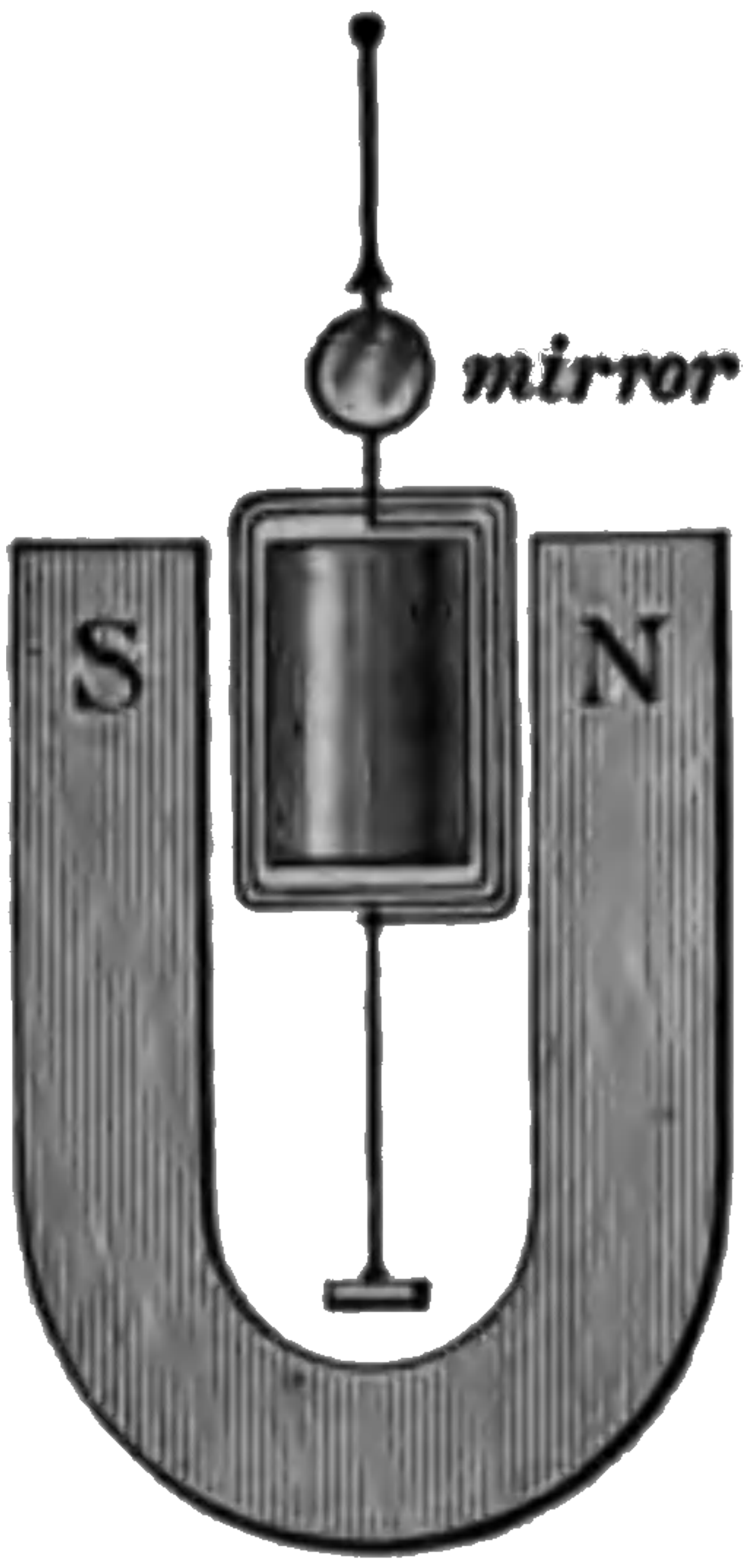


Fig. 125.

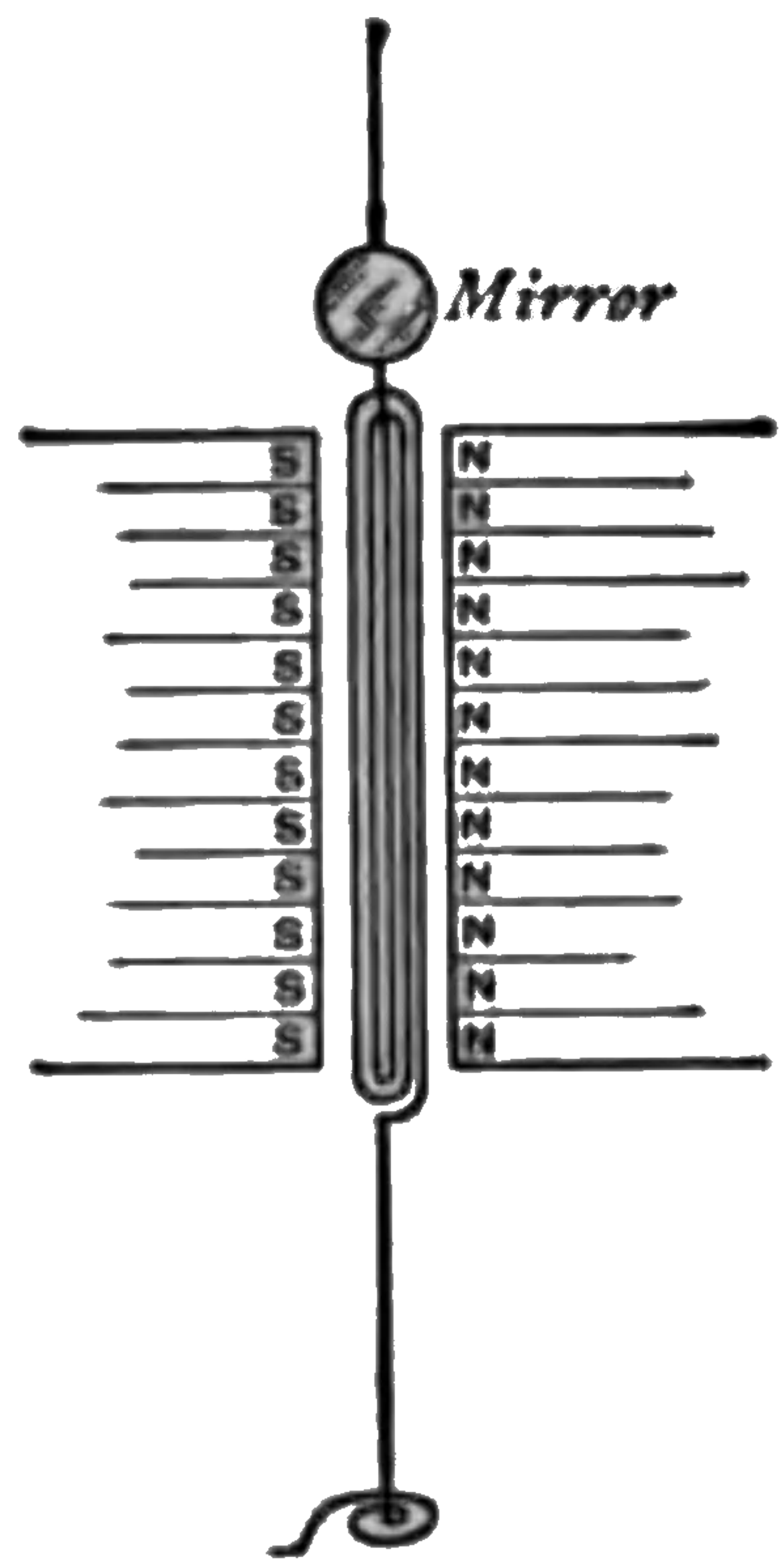


Fig. 126.

Most recent is the suspended-coil galvanometer of Ayrton and Mather (Fig. 126). Here the suspended coil is formed as an elongated loop with no

aperture between its sides. Consequently the poles of the magnets may be brought very close together; and these are made up of a number of flat steel magnets of nearly circular form piled up on one another. One of these instruments, with mirror and scale, will show a deflexion of one scale division, with a current less than one ninety-millionth part of 1 *ampere*.

Strong currents must not be passed through very sensitive galvanometers, for, even if they are not spoiled, the deflexions of the needle will be too large to give accurate measurements. In such cases the galvanometer is used with a *shunt*, or coil of wire arranged so that the greater part of the current shall flow through it, and pass the galvanometer by, only a small portion of the current actually traversing the coils of the instrument. The resistance of the shunt must bear a known ratio to the resistance of the instrument, according to the principle laid down in Art. 409 about branched circuits.

217. Differential Galvanometer.—For the purpose of comparing two currents a galvanometer is sometimes employed, in which the coil consists of *two* separate wires wound side by side. If two equal currents are sent in opposite directions through these wires, the needle will not move. If the currents are, however, unequal, then the needle will be moved by the stronger of them, with an intensity corresponding to the *difference* of the strengths of the two currents.

218. Ballistic Galvanometer.—In order to measure the strength of currents which last only a very short time, galvanometers are employed in which the needle takes a relatively long time to swing. This is the case with long or heavy needles; or the needles may be weighted by enclosing them in leaden cases. As the needle swings slowly round, it adds up, as it were, the varying impulses received during the passage of a transient current. *The sine of half the angle of the first swing is proportional to the quantity of electricity that has flowed through the coil.* The

charge of a condenser may thus be measured by discharging it through a ballistic galvanometer (see Art. 418*b*). The needle must not be damped.

219. Methods of Damping: Aperiodic Galvanometers.—To prevent the needle from swinging to and fro for a long time devices are used to *damp* the motion. These are:—

(*a*) *Air Damping.*—A light vane attached to needle beats against the air and damps the motion. In mirror instruments the mirror itself damps, particularly if confined in a narrow chamber.

(*b*) *Oil Damping.*—A vane dips into oil.

(*c*) *Magnetic Damping.*—If the needle swings close to or inside a mass of copper, it will soon come to rest by reason of the eddy-currents (Art. 457) induced in the copper. Eddy-currents damp the motion of the suspended coil in instruments of that class.

The period of swing can be reduced by diminishing the weight and leverage of the moving parts so as to lessen their moment of inertia. It can also be lessened (at the expense of the sensitiveness of the instrument) by increasing the controlling forces. An instrument so well damped as to come to rest without getting up a periodic swing is called an *aperiodic* or *dead-beat* instrument.

120. Voltmeters, or Potential Galvanometers.—If any galvanometer be constructed with a very long thin wire of high resistance as its coil, very little current will flow through it, but what little current flows will be exactly proportional to the potential difference that may be applied to the two ends of its circuit. Such a galvanometer, suitably provided with a scale, will indicate the number of *volts* between its terminals. Many forms of voltmeter-galvanometers exist, but they all agree in the essential of having a coil of a high resistance—sometimes several thousand ohms. The suspended-coil galvanometers described in Art. 216 make excellent voltmeters.

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commerce there are a number in which there is neither magnet nor iron, but which depend upon the mutual force between a fixed and a movable coil traversed by the current. These are dealt with in Art. 394, and are suitable for alternate currents as well as continuous currents. Of this kind are Siemens' electrodynamometer and the Kelvin balances.

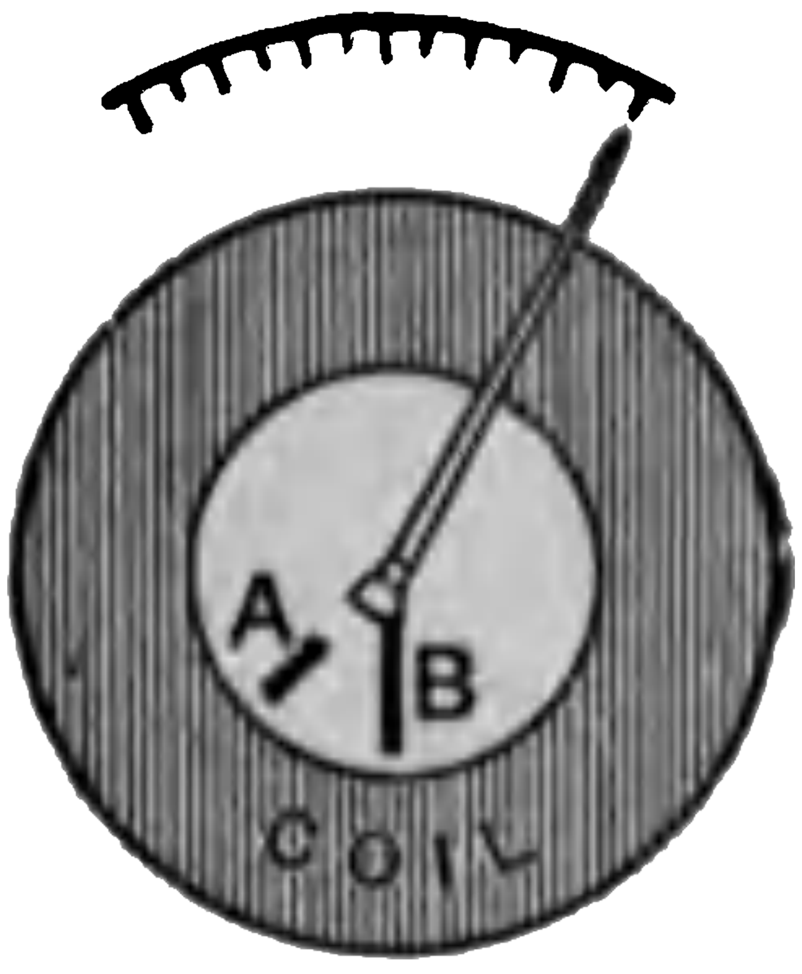


Fig. 128.

Other instruments depend upon the magnetic properties of iron under the influence of the current. Of this class are the Schuckert instruments represented in Fig. 128. An index pivoted in the axis of an open coil carries a light strip of soft iron seen endways at B. Another strip A is fixed within the coil. The current flowing round the coil magnetizes these strips and they repel one another. Gravity is here the controlling force.

Lesson XVIII. — *Currents produced by Induction*

222. Faraday's Discovery. — In 1831 Faraday discovered that currents can be induced in a closed circuit by moving magnets near it, or by moving the circuit across the magnetic field; and he followed up this discovery by finding that a current whose strength is changing may induce a secondary current in a closed circuit near it. Such currents, whether generated by magnets or by other currents, are known as **Induction Currents.** And the action of a magnet or current in producing such induced currents is termed **electromagnetic** (or magneto-electric) **induction,*** or simply induction. Upon

* The student must not confuse this electromagnetic induction with the phenomenon of the electrostatic induction of one *charge* of electricity by another *charge*, as explained in Lesson III., and which has nothing to do with *currents*. Formerly, before the identity of the electricity derived from different sources was understood (Art. 246), electricity derived thus

this principle are based the modern *dynamo machines* for generating electric currents mechanically, as well as *induction coils*, alternate-current *transformers*, and other appliances.

223. Induction of Currents by Magnets.—If a coil of insulated wire be connected in circuit with a sufficiently delicate galvanometer, and a magnet be inserted rapidly into the hollow of the coil (as in Fig. 129), a momentary current is observed to flow round the circuit while the magnet is being moved into the coil. So long as the magnet lies motionless in the coil it induces no currents. But if it be rapidly pulled out of the coil another momentary current will be observed to flow, and in the opposite direction to the former. The induced current caused by inserting the magnet is an *inverse current*, or is in the opposite direction to that which would magnetize the magnet with its existing polarity. The induced current caused by withdrawing the magnet is a *direct* current.



Fig. 129.

Precisely the same effect is produced if the coil be moved towards the magnet as if the magnet were moved toward the coil. The more rapid the motion is, the stronger are the induced currents.

The magnet does not grow any weaker by being so used, for the real source of the electrical energy generated is the mechanical energy spent in the motion.

from the motion of magnets was termed *magneto-electricity*. For most purposes the adjectives *magneto-electric* and *electro-magnetic* are synonymous. The production of electricity from magnetism, and of magnetism from electricity, are, it is true, two distinct operations; but both are included in the branch of science denominated *Electromagnetics*.

If the circuit is not closed, no currents are produced; but the relative motion of coil and magnet will still set up electromotive-forces, *tending* to produce currents.

Faraday discovered these effects to be connected with the magnetic field surrounding the magnet. He showed that no effect was produced unless the circuit cut across the invisible magnetic lines of the magnet.

224. Induction of Currents by Currents. — Faraday also showed that the approach or recession of a current might induce a current in a closed circuit near it. This may be conveniently shown as an experiment by the apparatus of Fig. 130.

A coil of insulated wire P is connected in circuit with a battery B of two or three cells, and a key K to turn the

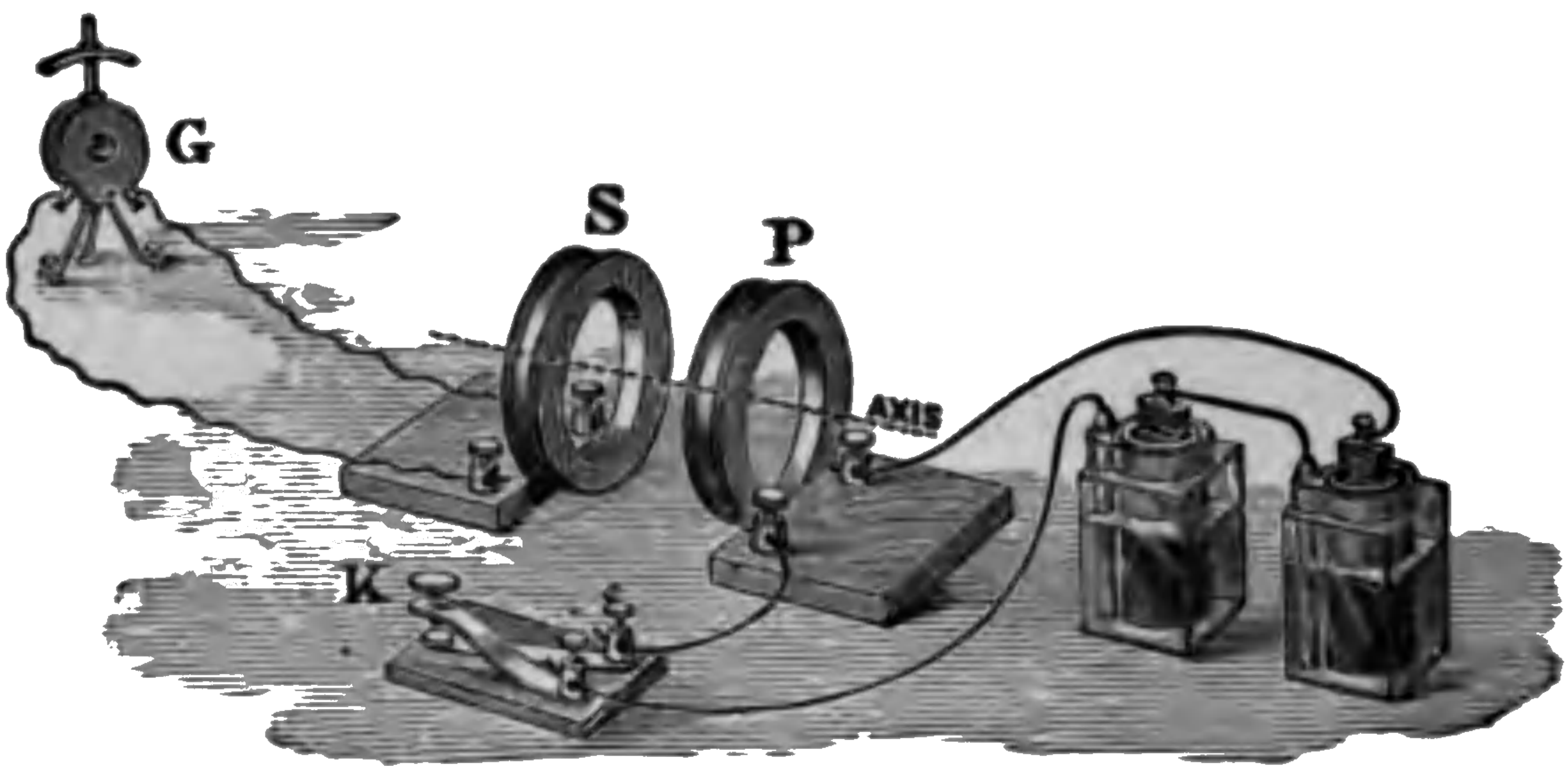


Fig. 130.

current on or off. A second coil S, entirely unconnected with the first, is joined up with wires to a sensitive galvanometer G. We know (Art. 202) that a coil of wire in which a current is circulating acts like a magnet. And we find that if while the current is flowing in P, the coil is suddenly moved up toward S, a momentary current will be induced in S. If P is suddenly moved away from S another momentary current will be observed in the second circuit. The first of these two momentary currents is an "inverse" one, while the second one is

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225. Fundamental Laws of Induction.—When we reflect that every circuit traversed by a current has a magnetic field of its own in which there are magnetic lines running through the circuit (Arts. 202 and 389), we shall see that the facts tabulated in the preceding paragraph may be summed up in the following fundamental laws:—

(i.) *A decrease in the number of lines which pass through a circuit induces a current round the circuit in the positive direction* (i.e. *produces a "direct" current*); *while an increase in the number of lines which pass through the circuit induces a current in the negative direction round the circuit* (i.e. *an "inverse" current*).

Here we suppose the *positive* direction along lines to be the direction along which a free N pole would tend to move, and the positive direction of the current that which the current must flow to increase the magnetic flux. Compare the "corkscrew" rule given on p. 183.

(ii.) *The total induced electromotive-force acting round a closed circuit is equal to the rate of decrease in the number of lines which pass through the circuit.*

Suppose at first the number of magnetic lines (Art. 119) passing through the circuit to be N_1, and that after a very short interval of time t the number becomes N_2, the average induced electromotive-force E is

$$E = \frac{N_1 - N_2}{t}.$$

By Ohm's law, $$C = E \div R,$$

therefore $$C = \frac{N_1 - N_2}{tR}.$$

If N_2 is greater than N_1, and there is an *increase* in the number of lines, then $N_1 - N_2$ will be a negative quantity, and C will have a negative sign, showing that the E.M.F. is an *inverse* one. A coil of 50 turns of wire cutting 1000 lines will produce the same effect as a coil of 5

turns cutting 10,000 lines, or of 1 turn cutting 50,000 lines.

To induce an electromotive-force equal to that of a single Daniell's cell would require that 110,000,000 lines should be cut in one second. As such large numbers are inconvenient to express the facts, the unit of E.M.F., the *volt*, has been chosen to correspond to the cutting of 100,000,000 lines per second.

> *Example.* — Suppose the number of magnetic lines to diminish from 800,000 to 0 in the $\frac{1}{50}$ of a second, the rate of diminution is 40,000,000 lines per second. And since 1 volt is taken as 10^8 lines per second, the average induced E.M.F. during that time will be 0·4 volt.

A reference to Fig. 176 will make this important law clearer. Suppose ABCD to be a wire circuit of which the piece AB can slide along DA and CB towards S and T. Let the vertical arrows represent vertical lines of force in a uniform magnetic field, and show (as is the case with the vertical components of the earth's lines of force in the northern hemisphere) the direction in which a N-pointing pole would move if free. The positive direction of these magnetic lines is therefore vertically downwards through the circuit. Now if AB slide towards ST with a uniform velocity it will cut a certain number of lines every second, and a certain number will be added during every second of time to the total number passing through the circuit. If N_1 be the number at the beginning, and N_2 that at the end of a circuit, $N_1 - N_2$ will be a negative quantity, and there will be generated an electromotive-force whose direction through the sliding piece is from A towards B.

It is important to note that *all* these inductive operations are really magnetic. In the experiment with the two coils P and S it is the magnetic lines of coil P which pass through coil S and set up the induced E.M.F. This is proved by the following further experiment. Take a bar of iron — a poker, or better still, a bundle of iron wires — and lay it along the dotted line so that its ends

pass through P and S. It will by its great magnetic permeability help to conduct the magnetic lines from P through S. And when it is so placed it will be found greatly to intensify the actions. In fact if P is many inches away from S, and the iron core is present, the inductive effects of turning the current on and off may be as great as if, in the absence of the core, P were pushed up close to S.

226. **Direction of Induced E.M.F.** — It is convenient to have rules for remembering the relations in direction between the magnetism, the motion, and the induced electromotive-force. Of such rules the following, due to Fleming, is most useful: *Let the forefinger of the right hand* (Fig. 131) *point in the direction of the magnetic lines; then turn the thumb in the direction of the motion: the middle finger bent at right angles to both thumb and forefinger will show the direction of the induced E.M.F.*

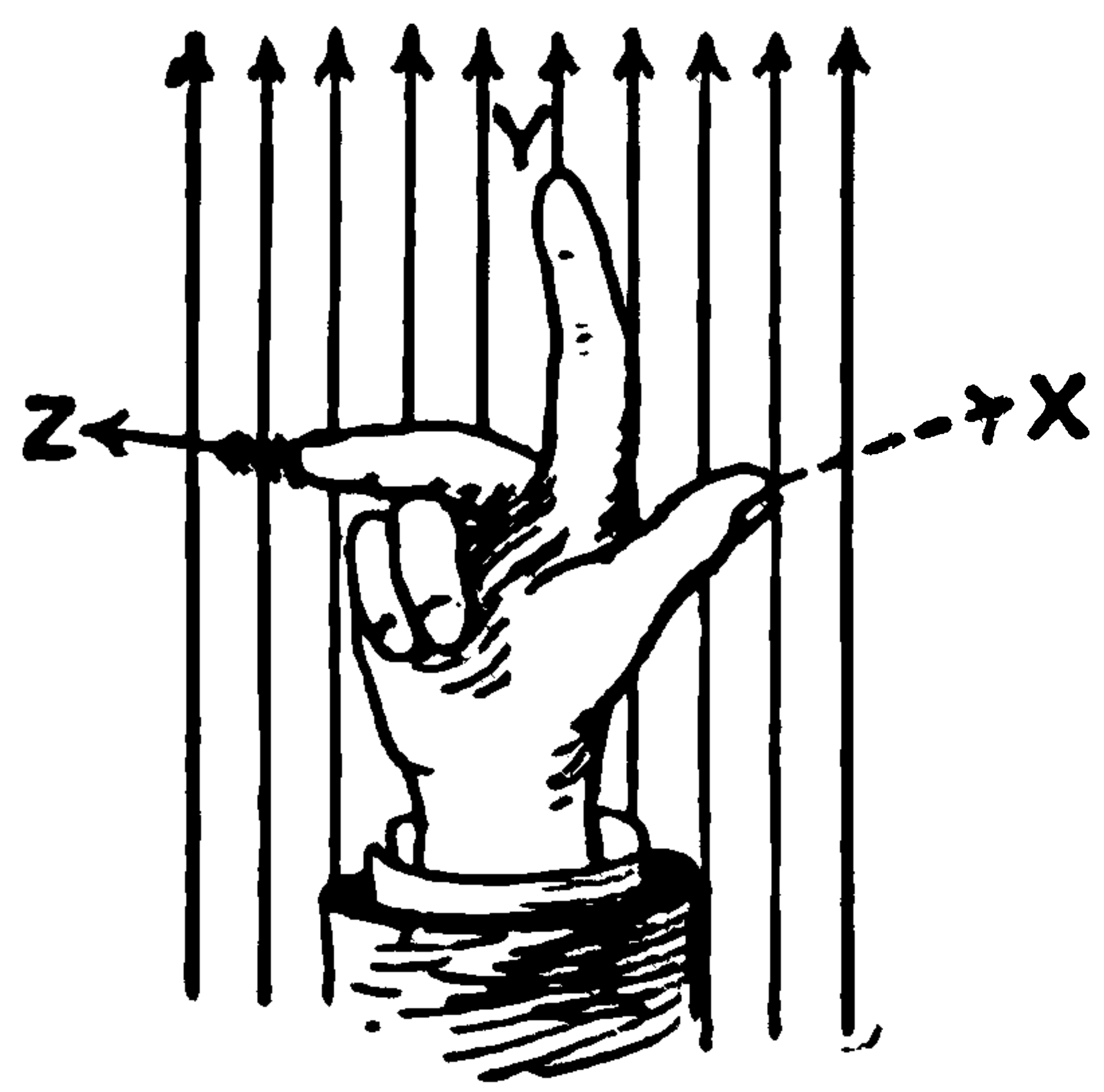


Fig. 131.

Another often given is an adaptation of Ampère's rule: *Suppose a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines, then if he and the conductor be moved towards his right hand he will be swimming with the current induced by this motion;* if he be moved towards his left hand, the current will be against him.

227. **Faraday's Disk Machine.** — Faraday constructed several magneto-electric machines, one of them consisting of a copper disk (Fig. 132) which he rotated between the poles of a steel magnet. The current flowed from shaft to rim or *vice versâ*, according to the sense of the rotation. It was conducted away by wires having sliding contacts. In other machines copper wire coils

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In all transformers the electromotive-forces generated in the secondary circuit are to those employed in the primary circuit, nearly in the same proportion as the relative numbers of turns in the two coils. For example, if the primary coil has 100 turns and the secondary has 2500 turns, the electromotive-force in the secondary circuit will be nearly twenty-five times as great as that used in the primary. By choosing the proper number of turns, the electromotive-force can be transformed either up or down.

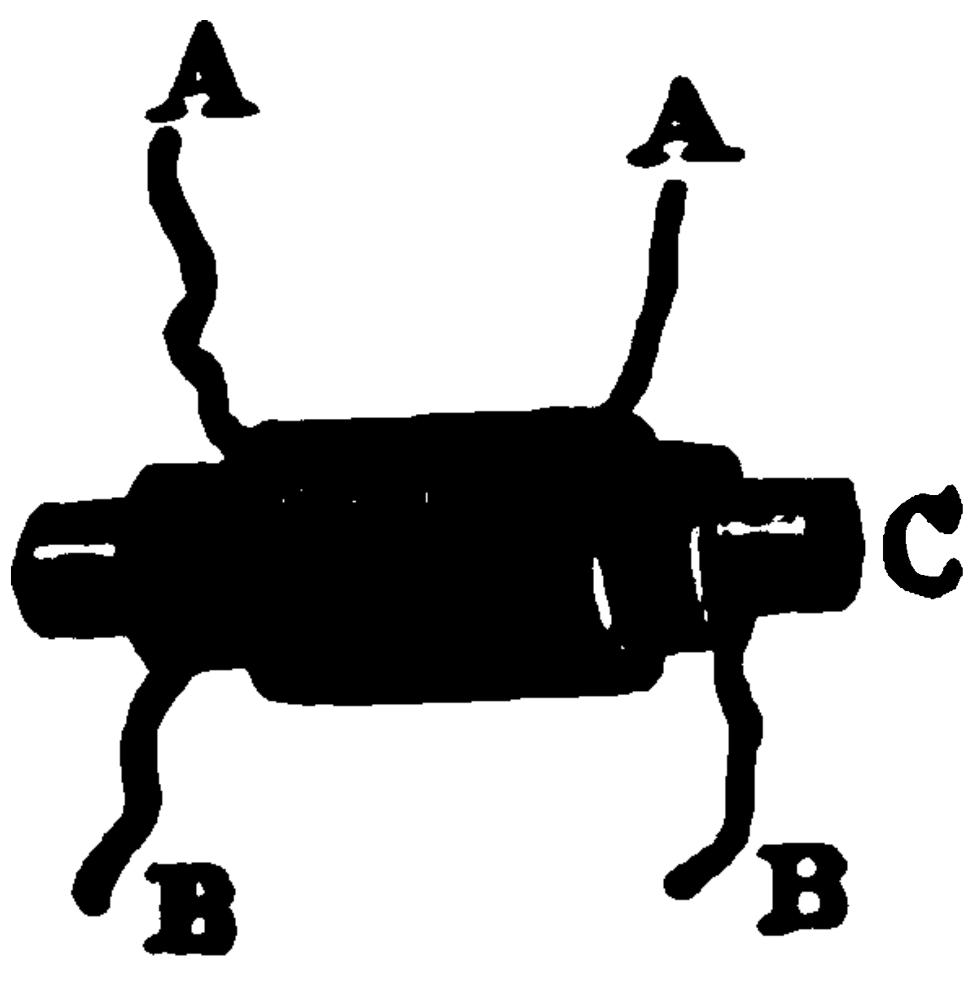


Fig. 184.

229. The Induction Coil.—In order to generate enormously high electromotive-forces which shall be able to send sparks across air spaces that ordinary batteries working at under 100 volts could not possibly pierce, advantage is taken of the transformer principle. To produce spark discharges there is used the apparatus depicted in Fig. 135, as improved by Callan, Sturgeon, Ruhmkorff, and others, and termed the **Induction Coil or Inductorium.** The induction coil consists of a cylindrical bobbin having a central iron core surrounded by a short inner or "primary" coil of stout wire, and by an outer "secondary" coil consisting of many thousand turns of very fine wire, very carefully insulated between its different parts. The primary circuit is joined to the terminals of a few powerful Grove's or Bunsen's cells, and in it are also included an interrupter and a commutator or key. The object of the interrupter, is to make and break the primary circuit in rapid succession. The result of this is at every "make" to induce in the outer "secondary" circuit a momentary inverse current, and at every "break" a powerful momentary direct current. As the number of magnetic lines created and destroyed at each "make" and "break" is the same, the two electromotive impulses are equal; but by the use of a condenser

the current at "make" is caused to take a considerable fraction of time to grow, whilst at "break" the cessation is instantaneous. The *rate* of cutting of the magnetic lines is therefore much greater at "break" than at "make." The induced electromotive-forces at "make" last longer, but are feebler, and do not suffice to send sparks. The currents at "break" manifest themselves as a brilliant torrent of sparks between the ends of the

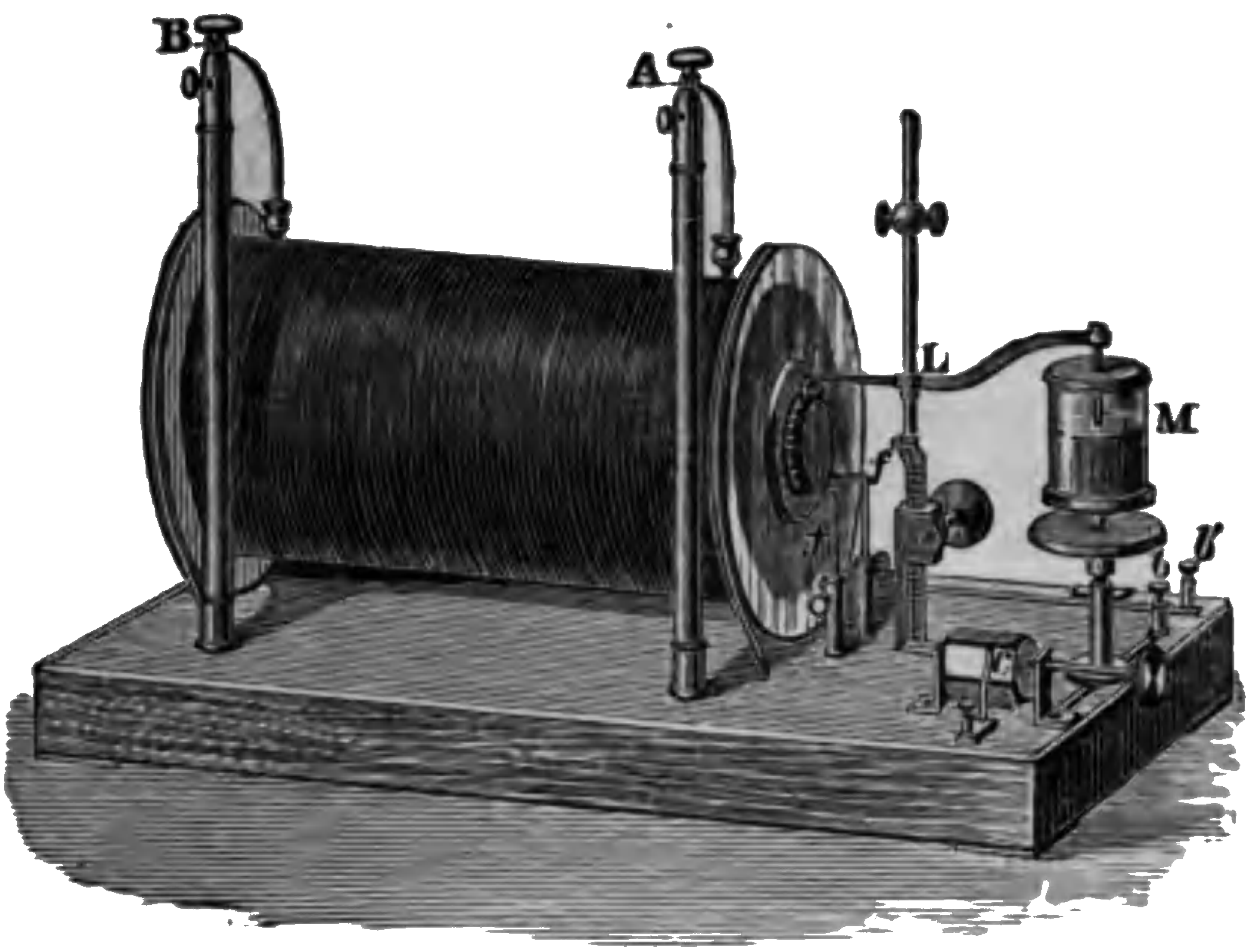


Fig. 135.

secondary wires when brought near enough together. The primary coil is made of stout wire, that it may carry strong magnetizing currents, and consists of few turns to keep the resistance low, and to avoid self-induction of the primary current on itself. The central iron core is for the purpose of increasing, by its great magnetic permeability, the number of lines of force that pass through the coils: it is usually made of a bundle of fine wires to avoid the induced currents which if it were a solid bar would be set circulating in it, and which would retard its rapidity of magnetization or demagnetization.

The secondary coil is made with many turns, in order that the coefficient of transformation may be large; and as the induced electromotive-force will be thousands of volts, the resistance of this coil will be immaterial, and it may be made of the thinnest wire that can conveniently be wound. In Mr. Spottiswoode's giant Induction Coil (which yields a spark of 42½ inches' length in air, when worked with 30 Grove's cells), the secondary coil contains 280 miles of wire, wound in 340,000 turns, and has a resistance of over 100,000 ohms.

The interrupters of induction coils are usually self-acting. That of Foucault, shown with the coil in Fig. 135, consists of an arm of brass L, which dips a platinum wire into a cup of mercury M, from which it draws the point out, so breaking circuit, in consequence of its other end being attracted toward the core of the coil whenever it is magnetized; the arm being drawn back again by a spring when, on the breaking of the circuit, the core ceases to be a magnet. A more common interrupter on small coils is a "break," consisting of a piece of thin steel which makes contact with a platinum point, and which is drawn back by the attraction of the core on the passing of a current; and so makes and breaks circuit by vibrating backwards and forwards just as does the hammer of an ordinary electric bell.

Associated with the primary circuit of a coil is usually a small *condenser* (see Art. 303), made of alternate layers of tinfoil and paraffined paper, into which the current flows whenever circuit is broken. The effect of the condenser is, as stated above, to suppress the "inverse" current at "make" and to increase greatly the direct electromotive-force at "break." The sparks are longer, and only pass one way. The condenser does this by the action known as electric *resonance* (see Art. 517).

230. Ruhmkorff's Reverser.—In order to cut off or reverse the direction of the battery current at will, Ruhmkorff applied the current-reverser, or reversing-

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232. Induction Currents from Earth's Magnetism. — It is easy to obtain induced currents from the earth's magnetism. A coil of fine wire joined to a sensitive galvanometer, when suddenly inverted, cuts the lines of the earth's magnetism, and induces a current.

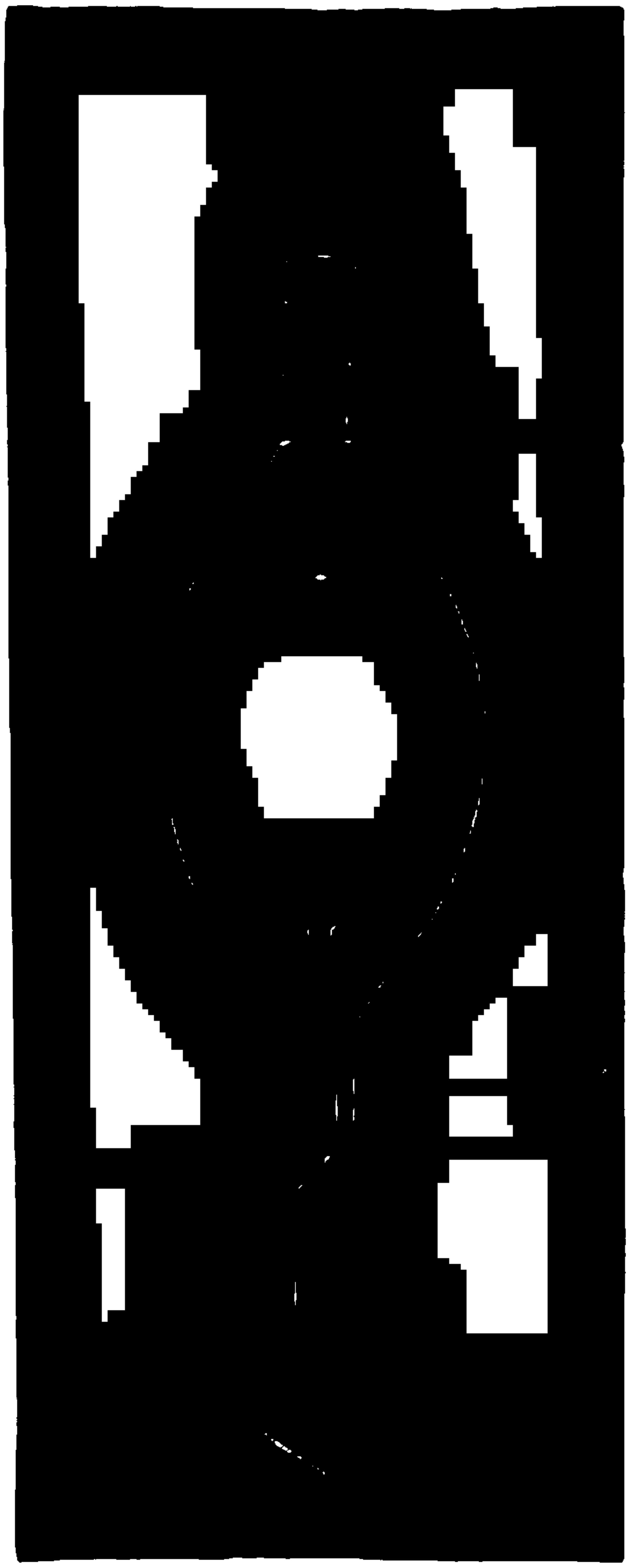


Fig. 187.

Faraday, indeed, applied this method to investigate the direction and number of magnetic lines. If a small wire coil be joined in circuit with a suitable galvanometer having a heavy needle, and the little coil be suddenly inverted while in a magnetic field, it will cut twice all the lines that pass through its own area, and the sine of half the angle of the first swing (Art. 418) will be proportional to the number of lines cut; for with a slow-moving needle, the total quantity of electricity that flows through the coils will be the integral whole of all the separate quantities conveyed by the induced currents, strong or weak, which flow round the circuit during the rapid process of cutting the lines. The little exploring coil acts therefore as a *magnetic proof-plane.* For small deflexions the first swing may be taken as a sufficient approximation instead of the sine of half the angle (see Art. 418).

If the circuit be moved parallel to itself across a uniform magnetic field there will be no induction currents, for just as many magnetic lines will be cut in moving ahead in front as are left behind. There will be no current in a wire moved parallel to itself along a line of force; nor, if it lie along such a line while a current is sent through it, will it experience any mechanical force.

233. Earth Currents.—The variations of the earth's magnetism, mentioned in Lesson XII., alter the number of magnetic lines which pass through the telegraphic circuits, and hence induce in them disturbances which are known as "earth currents." During magnetic storms the earth currents on the British lines of telegraph have been known to attain a strength of 40 milliamperes, which is stronger than the usual working currents. Feeble earth currents are observed every day, and are more or less periodic in character.

LESSON XIX.—*Chemical Actions of Currents*

234. Conducting Properties of Liquids.—In addition to the chemical actions inside the cells of the battery, which always accompany the production of a current, there are also chemical actions produced outside the battery when the current is caused to pass through certain liquids. Liquids may be divided into three classes —(1) *those which do not conduct at all*, such as turpentine and many oils, particularly petroleum; (2) *those which conduct without decomposition*, viz. mercury and other molten metals, which conduct just as solid metals do; (3) *those which are decomposed when they conduct a current*, viz. the dilute acids, solutions of metallic salts, and certain fused solid compounds.

235. Decomposition of Water.—In the year 1800 Carlisle and Nicholson discovered that the voltaic current could be passed through water, and that in passing through it decomposed a portion of the liquid into its

constituent gases. These gases appeared in bubbles on the ends of the wires which led the current into and out of the liquid; bubbles of *oxygen* gas appearing at the point where the current entered the liquid, and *hydrogen* bubbles where it left the liquid. It was soon found that a great many other liquids, particularly dilute acids and solutions of metallic salts, could be similarly decomposed by passing a current through them.

236. Electrolysis.—To this process of decomposing a liquid by means of an electric current Faraday gave the name of **electrolysis** (*i.e.* electric analysis); and those substances which are capable of being thus decomposed or "electrolyzed" he termed **electrolytes.**

The ends of the wires leading from and to the battery are called **electrodes**; and to distinguish them, that by which the current enters is called the **anode**, that by which it leaves the **kathode**. The vessel in which a liquid is placed for electrolysis is termed an *electrolytic cell.*

237. Electrolysis of Water.—Returning to the decomposition of water, we may remark that perfectly pure water appears not to conduct, but its resistance is greatly reduced by the addition of a few drops of sulphuric or of hydrochloric acid. The apparatus shown in Fig. 138 is suitable for this purpose. Here a battery of two cells (those shown are circular Bunsen's cells) is seen with its poles connected to two strips of metallic platinum as electrodes, which project up into a vessel containing the acidulated water. Two tubes closed at one end, which have been previously filled with water and inverted, receive the gases evolved at the electrodes. Platinum is preferred to other metals such as copper or iron for electrodes, since it is less oxidizable and resists every acid. It is found that there is almost exactly *twice* as much hydrogen gas (by volume) evolved at the kathode as there is of oxygen at the anode. This fact corresponds with the known chemical composition of water, which is

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238. Electrolysis of Sulphate of Copper. — We will take as another case the electrolysis of a solution of the well-known "blue vitriol" or sulphate of copper. If a few crystals of this substance are dissolved in water a blue liquid is obtained, which is easily electrolyzed between two electrodes of platinum foil, by the current from a single cell of any ordinary battery. The chemical formula for sulphate of copper is $CuSO_4$. The result of the electrolysis is to split it up into two parts. Metallic copper is carried forward by the current and deposited in a film upon the kathode, leaving behind at the anode "sulphion," an easily decomposed compound of sulphur and oxygen, which is immediately acted upon by the water forming sulphuric acid and oxygen. This oxygen is liberated in bubbles at the anode. The chemical changes are thus expressed:

$CuSO_4$			=	Cu	+	SO_4		
Sulphate of Copper			becomes	Copper	and	Sulphion;		
SO_4	+	H_2O	=			H_2SO_4	+	O
Sulphion	and	water	produce			Sulphuric acid	and	Oxygen.

In this way, as the current continues to flow, copper is continually withdrawn from the liquid and deposited on the kathode, and the liquid gets more and more acid. If copper electrodes are used, instead of platinum, no oxygen is given off at the anode, but the copper anode itself dissolves away into the liquid at exactly the same rate as the copper of the liquid is deposited on the kathode.

239. Anions and Kations. — The atoms which thus are severed from one another and carried invisibly by the current to the electrodes, and there deposited, are obviously of two classes; some are left behind at the anode, others are carried forward to the kathode. Faraday gave the name of ions to these wandering atoms; those left at the anode being **anions**, and those going to the kathode being **kations**. Anions are sometimes

regarded as "electronegative," because they move as if attracted toward the + pole of the battery, while the kations are regarded as "electropositive." Hydrogen and the metals are kations, moving apparently *with* the direction assumed as that of the current, and are deposited where the current leaves the electrolytic cell. The anions are oxygen, chlorine, etc. When, for example, chloride of tin is electrolyzed, metallic tin is deposited on the kathode, and chlorine gas is evolved at the anode.

240. Quantitative Laws of Electrolysis.

(i.) *The amount of chemical action is equal at all points of a circuit.* If two or more electrolytic cells are placed at different points of a simple circuit the amount of chemical action will be the same in all, for the same quantity of electricity flows past every point of the circuit in the same time. If all these cells contain acidulated water, the quantity, for example, of hydrogen set free in each will be the same; or, if they contain a solution of sulphate of copper, identical quantities of copper will be deposited in each. If some of the cells contain acidulated water, and others contain sulphate of copper, the weights of hydrogen and of copper will not be *equal*, but will be in chemically *equivalent* quantities.

(ii.) *The amount of an ion liberated at an electrode in a given time is proportional to the strength of the current.* A current of two *amperes* will cause just twice the quantity of chemical decomposition to take place as a current of one *ampere* would do in the same time.

(iii.) *The amount of an ion liberated at an electrode in one second is equal to the strength of the current multiplied by the "electro-chemical equivalent" of the ion.* It has been found by experiment that the passage of one *coulomb* of electricity through water liberates ·000010384 gramme of hydrogen. Hence, a current the strength of which is C (*amperes*) will liberate C × ·000010384 grammes of hydrogen per second. The quantity ·000010384 is

called the *electrochemical equivalent* of hydrogen. The "electrochemical equivalents" of other elements can be easily calculated if their chemical "equivalent" is known. Thus the chemical "equivalent" * of copper is 31·59; multiplying this by ·000010384 we get as the electrochemical equivalent of copper the value ·0003281 (gramme).

Table of Electrochemical Equivalents, etc.

Element.	Atomic Weight.	Valency.	Chemical Equivalent.	Electrochemical Equivalent (grammes per *coulomb*).
Electropositive—				
Hydrogen . . .	1	1	1	0·000010384
Potassium . . .	39·08	1	39·08	0·0004058
Sodium . . .	23·	1	23·	0·0002388
Gold	196·2	3	65·4	0·0006791
Silver	107·67	1	107·67	0·0011181
Copper (Cupric) . .	63·18	2	31·59	0·0003281
" (Cuprous) .	63·18	1	63·18	0·0006562
Mercury (Mercuric) .	199·8	2	99·9	0·0010374
" (Mercurous)	199·8	1	199·8	0·0020748
Tin (Stannic) . .	117·8	4	29·45	0·0003058
" (Stannous) . .	117·8	2	58·9	0·0006116
Iron (Ferrous) . .	55·9	2	27·95	0·0002902
" (Ferric) . .	55·9	(3)	18·64	0·0001935
Nickel	58·6	2	29·3	0·0003043
Zinc	64·9	2	32·45	0·00033698
Lead	206·4	2	103·2	0·0010716
Electronegative—				
Oxygen . . .	15·96	2	7·98	0·00008286
Chlorine . . .	35·37	1	35·37	0·0003678
Iodine	126·54	1	126·54	0·0013140
Bromine . . .	79·76	1	79·76	0·0008282
Nitrogen . . .	14·01	3	4·67	0·00004849

* The chemical *equivalent* must not be confounded with the *atomic weight*. The atomic weight of copper is 63, that is to say, its atoms are 63 times as heavy as atoms of hydrogen. But in chemical combinations one

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tameter, provided the tubes to collect the gases be graduated, so as to measure the quantities evolved. The weight of each measured cubic centimetre of hydrogen (at the standard temperature of 0° C., and pressure of 760 millims.) is known to be ·00008988 grammes. Hence, if the number of cubic centimetres liberated during a given time by a current of unknown strength be ascertained, the mean strength of the current can be calculated by first reducing the volume to weight, and then dividing by the electrochemical equivalent, and by the time. Each *coulomb* of electricity liberates in its flow ·1155 cubic centimetres of hydrogen, and ·0577 c.c. of oxygen. If these gases are collected together in a *mixed-gas voltameter* there will be ·1732 c.c. of the mixed gases evolved for every *coulomb* of electricity which passes. To decompose 9 grammes of water, liberating 1 gramme of H and 8 grammes of O, requires 96,302 *coulombs* to be sent through the liquid with an electromotive-force of at least 1·47 *volts* (see Art. 487).

244. Copper and Silver Voltameters.—As mentioned above, if sulphate of copper is electrolyzed between two electrodes of copper, the anode is slowly dissolved, and the kathode receives an equal quantity of copper as a deposit on its surface. One *coulomb* of electricity will cause ·0003281 gramme to be deposited; and to deposit one gramme weight requires a total quantity of 3048 *coulombs* to flow through the electrodes. A current of one *ampere* deposits in one hour 1·177 grammes of copper, or 4·0248 grammes of silver.

By weighing one of the electrodes before and after the passage of a current, the gain (or loss) will be proportional to the quantity of electricity that has passed. In 1879 Edison, the inventor, applied this method for measuring the quantity of electricity supplied to houses for electric lights in them; a small copper voltameter being placed in a branch of the circuit which supplied the house, to serve as a meter. Various other kinds of

supply meters have been proposed, having clockwork counters, rolling integrating disks, and other mechanical devices to add up the total quantity of electricity conveyed by the current (see Art. 442).

245. Comparison of Voltameters with Galvanometers. —It will be seen that both *Galvanometers* and *Voltameters* are intended to measure the strength of currents, one by magnetic, the other by chemical means. Faraday demonstrated that the magnetic and the chemical actions of a current are proportional to one another. In Fig. 139 is shown a circuit that is branched so that the current divides, part going through a branch of small resistance *r* and part through a branch of larger resistance R. The current will divide, the greater part going by the path of lesser resistance. Three amperemeters are used. It will be found that the number of *amperes* in the main circuit is equal to the sum of the *amperes* in the two branches. In Fig. 140 the three amperemeters have been replaced by three copper voltameters. The weight of copper deposited in the voltameter A in the main circuit will be found to be equal to the sum of the weights deposited in B and C in the two branches. A galvanometer shows, however, the strength of the current at any moment, and its variations in strength from one moment to another, by the position of the needle. In a voltameter, a varying current may liberate the atoms of copper or the bubbles of gas rapidly at one moment, and slowly the next, but all the varying quantities will be simply added together in the total yield.

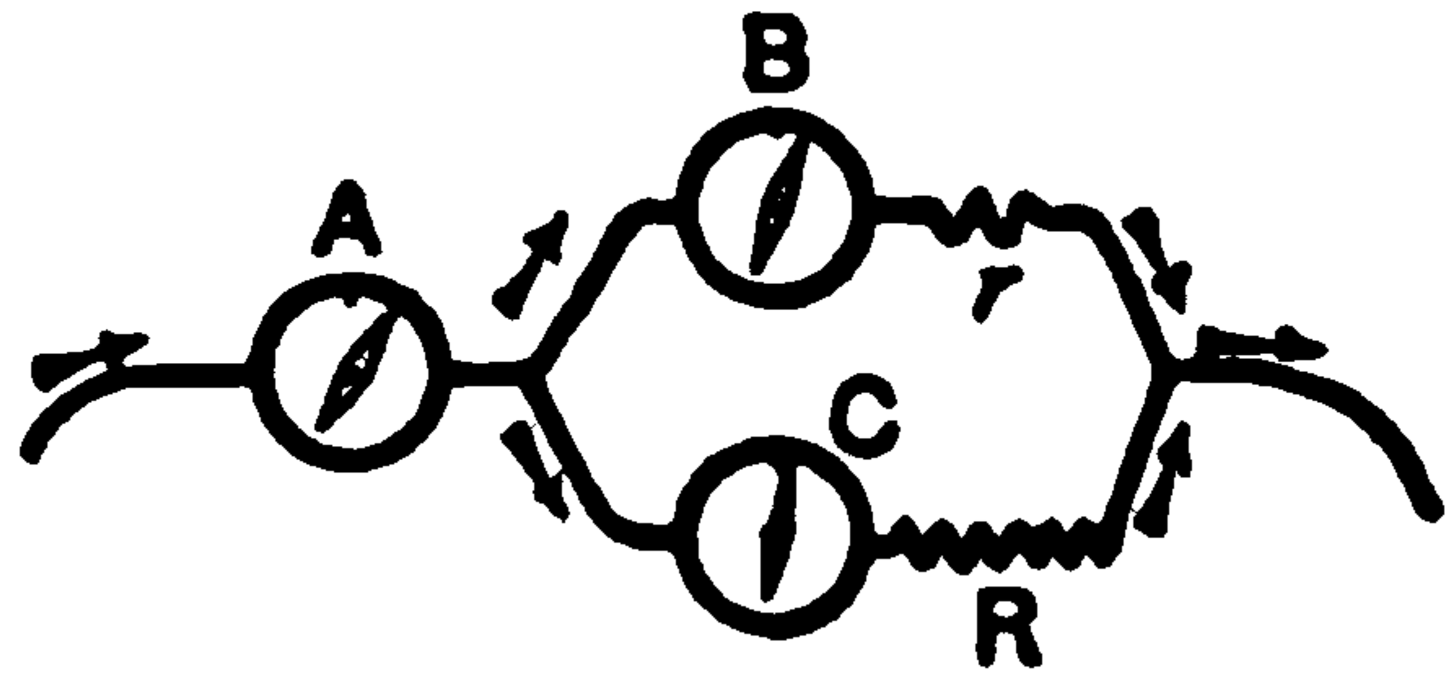


Fig. 139.

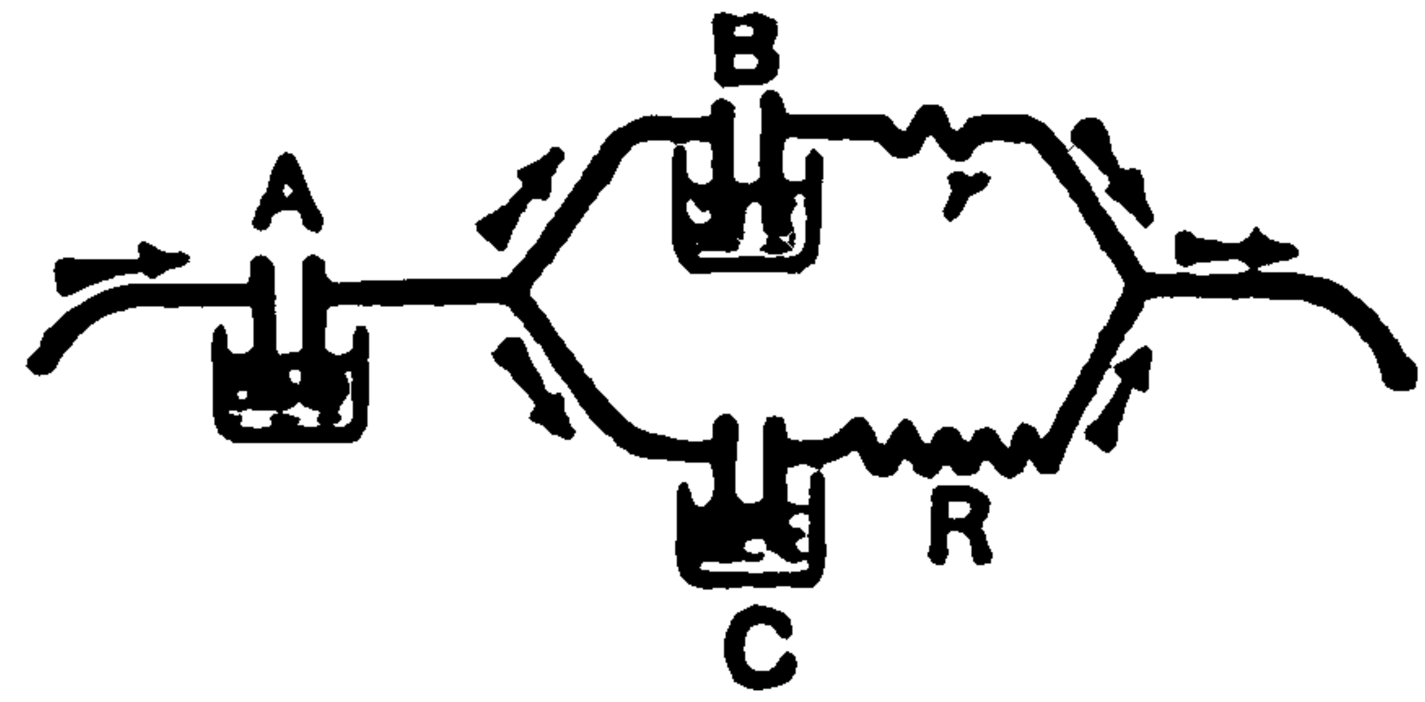


Fig. 140.

In fact, the voltameter gives us the "time integral" of the current. It tells us *what quantity of electricity* has flowed through it during the experiment, rather than *how strong the current was* at any one moment.

246. Chemical Test for Weak Currents.—A very feeble current suffices to produce a perceptible amount of change in certain chemical substances. If a few crystals of the white salt *iodide of potassium* are dissolved in water, and then a little starch paste is added, a very sensitive electrolyte is obtained, which turns to a dark blue colour at the anode when a very weak current passes through it. The decomposition of the salt liberates iodine at the anode, which, acting on the starch, forms a coloured compound. White blotting-paper, dipped into the prepared liquid, and then laid on the kathode and touched by the anode, affords a convenient way of examining the discoloration due to a current. A solution of ferrocyanide of potassium affords when using an anode of iron the well-known tint of Prussian blue. Bain proposed to utilize this in a Chemical Writing Telegraph, the short and long currents transmitted along the line being thus recorded in blue marks on a strip of prepared paper, drawn along by clockwork under an iron stylus joined to the positive wire. Faraday showed that chemical discoloration of paper moistened with starch and iodide of potassium was produced by the passage of electricity from sources of all different kinds—frictional, voltaic, thermo-electric, and magneto-electric,—even by that evolved by the Torpedo and the Gymnotus. In fact, he relied on this chemical test as one proof of the identity of the different kinds.

247. Internal and External Actions.—In an earlier lesson it was shown that the quantity of chemical action inside the cells of the battery was proportional to the current. Hence, Law (i.) of Art. 240 applies both to the portion of the circuit within the battery and to that without it.

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will be the product of C and – E, or – CE, the negative sign indicating that the circuit is losing energy, part of its energy being absorbed in the cell in doing chemical work. If current is sent backwards through a Daniell cell the chemical processes are reversed, copper is dissolved and zinc is deposited. But all cells are not reversible in their chemical action.

A theory of electrolysis, and some examples of its application, are given in Art. 488 on Electro-chemistry.

LESSON XX.—*Physical and Physiological Effects of the Current*

249. Molecular Actions.—Metal conductors, when subjected to the prolonged action of currents, undergo slow molecular changes. Wires of copper and brass gradually become brittle under its influence. During the passage of the current through metallic wires their cohesion is temporarily lessened, and there also appears to be a decrease in their coefficient of elasticity. It was thought by Edlund that a definite elongation could be observed in strained wires when a current was passed through them; but it has not yet been satisfactorily shown that this elongation is independent of the elongation due to the heating of the wire owing to the resistance it opposes to the current.

250. Electric Osmose.—Porret observed that if a strong current is led into certain liquids, as if to electrolyze them, a porous partition being placed between the electrodes, the current mechanically carries part of the liquid through the porous diaphragm, so that the liquid is forced up to a higher level on one side than on the other. This phenomenon, known as *electric osmose*, is most manifest when badly-conducting liquids, such as alcohol and bisulphide of carbon, are used. The transfer through the diaphragm takes place in the direction of

the current; that is to say, the liquid is higher about the kathode than round the anode.

251. Electric Distillation. — Closely connected with the preceding phenomenon is that of the *electric distillation* of liquids. It was noticed by Beccaria that an electrified liquid evaporated more rapidly than one not electrified. Gernez has recently shown that in a bent closed tube, containing two portions of liquid, one of which is made highly + and the other highly −, the liquid passes over from + to −. This apparent distillation is not due to difference of temperature, nor does it depend on the extent of surface exposed, but is effected by a slow creeping of the liquid along the interior surface of the glass tubes. Bad conductors, such as turpentine, do not thus pass over.

252. Diaphragm Currents. — Professor Quincke discovered that a current is set up in a liquid when it is forced by pressure through a porous diaphragm. This phenomenon may be regarded as the converse of electric osmose. The E.M.F. of the current varies with the pressure and with the nature of the diaphragm. When water was forced at a pressure of one atmosphere through sulphur, the difference of potential was over 9 volts. With diaphragms of porcelain and bladder the differences were only ·35 and ·01 volts respectively.

253. Electro-Capillary Phenomena. — If a horizontal glass tube, turned up at the ends, be filled with dilute acid, and a single drop of mercury be placed at about the middle of the tube, the passage of a current through the tube will cause the drop to move along towards the negative pole. It is believed that the liberation of very small quantities of gas by electrolysis at the surface where the mercury and acid meet alters the surface-tension very considerably, and thus a movement results from the capillary forces. Lippmann, Dewar, and others have constructed upon this principle *capillary electrometers*, in which the pressure of a column of liquid is made to bal-

ance the electro-capillary force exerted at the surface of contact of mercury and dilute acid, the electro-capillary force being nearly proportional to the electromotive-force when this does not exceed one volt. Fig. 142 shows the capillary electrometer of Dewar. A glass tube rests horizontally between two glass dishes in which holes have

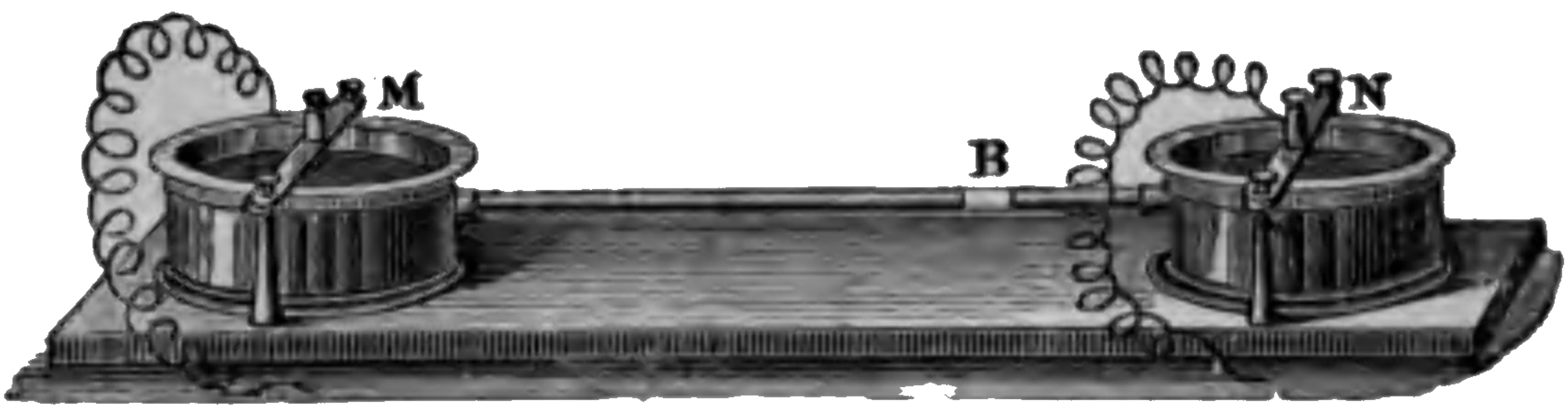


Fig. 142.

been bored to receive the ends of the tube. It is filled with mercury, and a single drop of dilute acid is placed in the tube. Platinum wires to serve as electrodes dip into the mercury in the dishes. An E.M.F. of only $\frac{1}{300}$ volt suffices to produce a measurable displacement of the drop. The direction of the displacement varies with that of the current.

254. Physiological Actions. — Currents of electricity passed through the limbs affect the nerves with certain painful sensations, and cause the muscles to undergo involuntary contractions. The sudden rush of even a small charge of electricity from a Leyden jar charged to a high potential, or from an induction coil (see Fig. 135), gives a sharp and painful *shock* to the system. The current from a few strong Grove's cells, conveyed through the body by grasping the terminals with moistened hands, gives a very different kind of sensation, not at all agreeable, of a prickling in the joints of the arms and shoulders, but not producing any spasmodic contractions, except it be in nervous or weakly persons, at the sudden making or breaking of the circuit. The difference between the two cases lies in the fact that the tissues of the body offer a very considerable resist-

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touched the moist tissues of the eye. Volta and Ritter heard musical sounds when a current was passed through the ears; and Humboldt found a sensation to be produced in the organs of smell when a current was passed from the nostril to the soft palate. Each of the specialized senses can be stimulated into activity by the current. Man possesses no specialized sense for the perception of electrical forces, as he does for light and for sound; but there is no reason for denying the possibility that some of the lower creatures may be endowed with a special electrical sense.

The following experiment shows the effect of feeble currents on cold-blooded creatures. If a copper (or silver) coin be laid on a piece of sheet zinc, and a common garden snail be set to crawl over the zinc, directly it comes into contact with the copper it will suddenly pull in its horns, and shrink in its body. If it is set to crawl over two copper wires, which are then placed in contact with a feeble voltaic cell, it immediately announces the establishment of a current by a similar contraction.*

255. Muscular Contractions.—In 1678 Swammerdam showed to the Grand Duke of Tuscany that when a portion of muscle of a frog's leg hanging by a thread of nerve bound with silver wire was held over a copper support, so that both nerve and wire touched the copper, the muscle immediately contracted. More than a century later Galvani's attention was drawn to the subject by his observation of spasmodic contractions in the legs of freshly-killed frogs under the influence of the "return-shock" experienced every time a neighbouring electric machine was discharged. Unaware of Swammerdam's experiment, he discovered in 1786 the fact (alluded to in Art. 163 as leading ultimately to the discovery of the Voltaic Pile) that when nerve and muscle touch two dissimilar metals in contact with one another a contraction of the muscle takes place. The limbs of the frog,

* It will scarcely be credited that a certain Jules Allx once seriously proposed a system of telegraphy based on this physiological phenomenon.

prepared as directed by Galvani, are shown in Fig. 143. After the animal has been killed the hind limbs are detached and skinned; the crural nerves and their attachments to the lumbar vertebræ remaining. For some hours after death the limbs retain their contractile power. The frog's limbs thus prepared form an excessively delicate galvanoscope: with them, for example, the excessively

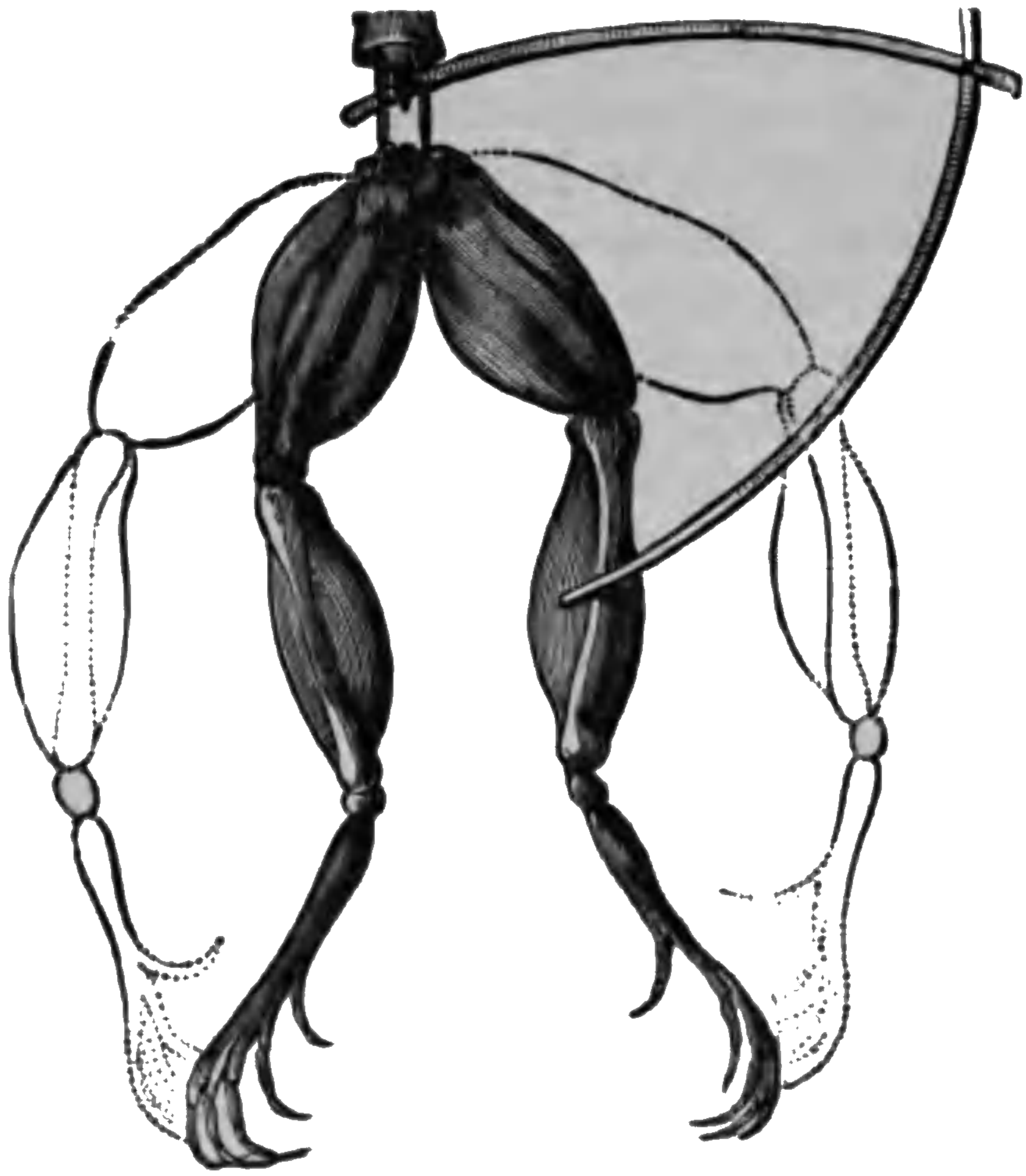


Fig. 143.

delicate induction-currents of the telephone (Lesson LIII.) can be shown, though the most sensitive galvanometers barely detect them. Galvani and Aldini proved that other creatures undergo like effects. With a pile of 100 pairs Aldini experimented on newly-killed sheep, oxen, and rabbits, and found them to suffer spasmodic muscular contractions. Humboldt proved the same on fishes; and Zanotti, by sending a current through a newly-killed grasshopper, caused it to emit its familiar chirp. Aldini,

and later Dr. Ure of Glasgow, experimented on the bodies of executed criminals, with a success terrible to behold. The facial muscles underwent horrible contortions, and the chest heaved with the contraction of the diaphragm. The small muscles attached to the roots of the hairs of the head appear to be markedly sensitive to electrical conditions from the readiness with which electrification causes the hair to stand on end.

The resistance of the human body to the flow of electric current through it depends mainly on the dryness of the skin. It may vary from 10,000, down to 300 *ohms* when the skin is moist. From experiments made in America in connexion with the execution of criminals, it was found that the average resistance of the human body is 2500 *ohms*, and that 3000 (alternating) volts applied between the head and spine caused instantaneous death.

A current of as much as 20 milliamperes produces terrible muscular contractions, whilst a current of 2 amperes traversing a vital part is almost certainly fatal. The effect of the current is twofold; in the first place it acts upon the nerves, causing spasms, secondly it destroys the tissue either by burning or by electrolysis, the blood becoming coagulated. To restore a person who has been rendered insensible by an electric shock, all the same restoratives should be used as for a person drowned.

256. Conditions of Muscular Contraction.—To produce muscular contraction the current must traverse a portion of the nerve longitudinally. In a freshly-prepared frog the current causes a contraction only momentarily when the circuit is made or broken. A rapidly interrupted current will induce a second contraction before the first has had time to pass off, and the muscle may exhibit thus a continuous contraction resembling *tetanus*. The prepared frog after a short time becomes less sensitive, and a "direct" current (that is to say, one passing along the nerve in the direction from the brain to the muscle) only produces an effect when circuit is made, while an "in-

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tively connected by a water-contact with the terminals of a delicate galvanometer, a *current* is produced which lasts several hours: he even arranged a number of frogs' legs in series, like the cells of a battery, and thus increased the current. Matteucci showed that through the muscle alone there may be an electromotive-force. Du Bois Reymond has shown that if the end of a muscle be cut across, the *ends* of the muscular fibres of the transverse section are negative, and the *sides* of the muscular fibres are positive, and that this difference of potential will produce a current even while the muscle is at rest. To demonstrate this he employed a fine astatic galvanometer with 20,000 turns of wire in its coils; and to obviate errors arising from the contact of the ends of the wires with the tissues *unpolarizable electrodes* were used, made by plunging terminal zinc points into a saturated solution of sulphate of zinc, contained in a fine glass tube, the end of which was stopped with a porous plug of moistened china clay. Normal muscle at rest shows no current whatever between its parts. Injured muscle at rest shows a current from the injured toward the uninjured part (returning toward the injured part through the galvanometer). Normal muscle when active shows a current from the active part toward the resting part. Du Bois Reymond obtained currents from his own muscles by dipping the tips of his forefingers into two cups of salt water communicating with the galvanometer terminals. A sudden contraction of the muscles of either arm produced a current from the contracted toward the uncontracted muscles. Dewar has shown that when light falls upon the retina of the eye an electric current is set up in the optic nerve. In the skin, and especially in the skin of the common eel, there is an electromotive-force from without inwards.

258. **Surgical Applications.**—Electric currents have been successfully employed as an adjunct in restoring persons rescued from drowning; the contraction of the

diaphragm and chest muscles serving to start respiration. Since the discovery of the Leyden jar many attempts have been made to establish an electrical medical treatment. Discontinuous currents, particularly those furnished by small induction-coils and magneto-electric machines, are employed by practitioners to stimulate the nerves in paralysis and other affections. Electric currents should not be used at all except with great care, and under the direction of regularly-trained surgeons. It is not out of place to enter an earnest caution on this head against the numerous quack doctors who deceive the unwary with magnetic and galvanic "appliances." In many cases these much-advertised shams have done incalculable harm: in the very few cases where some fancied good has accrued the curative agent is probably not magnetism, but flannel!

The usual pathological dose of current is from 2 to 10 milliamperes. Apparatus pretending to cure, and incapable of furnishing such currents, is worthless. Continuous currents appear to produce a sedative effect around the anode, which is of service in neuralgia and painful affections, and an increase in irritability around the kathode, useful in cases of paralysis. The continuous current is also employed electrolytically to disperse tumours. Alternate currents, and rapidly interrupted uni-directional currents stimulate the nerves.

Part Second

CHAPTER IV

ELECTROSTATICS

Lesson XXI. — *Theory of Potential*

259. By the lessons in Chapter I. the student will have obtained some elementary notions upon the existence and measurement of definite quantities of electricity. In the present lesson, which is both one of the hardest and one of the most important to the beginner, and which he must therefore study the more carefully, the laws which concern the magnitude of electrical quantities and their measurement are more fully explained. In no branch of knowledge is it more true than in electricity, that "science is measurement." That part of the science of electricity which deals with the measurement of charges of electricity is called **Electrostatics**. We shall begin by discussing first the simple laws of electric force, which were brought to light in Chapter I. by simple experimental means.

260. First Law of Electrostatics. — *Electric charges of similar sign repel one another, but electric charges of opposite signs attract one another.* The fundamental facts expressed in this Law were fully explained in Lesson I.

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Electricians of all nations have agreed in adopting a system which is based upon three fundamental units: viz. the **Centimetre** for a unit of *length;* the **Gramme** for a unit of *mass;* the **Second** for a unit of *time.* All other units can be derived from these, as is explained in the note at the end of this lesson. Now, amongst the derived units of this system is the unit of *force,* named the **Dyne**, which is that force which, acting for one second on a mass of one gramme, imparts to it a velocity of one centimetre per second. Taking the dyne then as the unit of force, and the centimetre as the unit of length (or distance), we must find a unit of electric quantity to agree with these in our equation. It is quite clear that if q, q', and r were each made equal to 1 (that is, if we took two charges of value 1 each, and placed them one centimetre apart), the value of $\frac{q \times q'}{r^2}$ would be $\frac{1 \times 1}{1 \times 1}$, which is equal to 1. Hence we adopt, as our Definition of a *Unit of Electricity*,* the following, which we briefly gave at the end of Lesson II. *One Unit of Electricity is that quantity which, when placed at a distance of one centimetre (in air) from a similar and equal quantity, repels it with a force of one dyne.*

An example will aid the student to understand the application of Coulomb's Law.

Example.—Two small spheres, charged respectively with 6 units and 8 units of + electricity, are placed 4 centimetres apart; find what force they exert on one another. By the formula, $f = \frac{q \times q'}{r^2}$, we find $f = \frac{6 \times 8}{4^2} = \frac{48}{16} = 3$ dynes.

The force in the above example would clearly be a force of repulsion. Had one of these charges been

* That is one unit, in the *electrostatic* system. It is only $\frac{1}{3000000000}$ of the quantity called 1 *coulomb.*

negative, the product $q \times q'$ would have had a $-$ value, and the answer would have come out as *minus* 3 dynes. The presence of the negative sign, therefore, prefixed to a force, will indicate that it is a force of *attraction*, whilst the + sign would signify a force of *repulsion*.

The intensity of an electric field (Art. 266) being measured by the force it exerts on a unit charge, it at once follows that at a distance of r (in air) from a charge q the intensity of the electric field due to that charge will be q/r^2. If the intervening medium be not air, but have a specific dielectric capacity k, the field will be only q/kr^2.

263. Potential. — We must next define the term *potential*, as applied to electric forces; but to make the meaning plain a little preliminary explanation is necessary. Suppose we had a + charge on a small insulated sphere A (see Fig. 144), placed by itself far from all other electric charges and conductors. If we were to bring another positively-charged body B near it, A would repel B. But the repelling force would depend on the *quantity* of the new charge, and on the *distance* at which it was

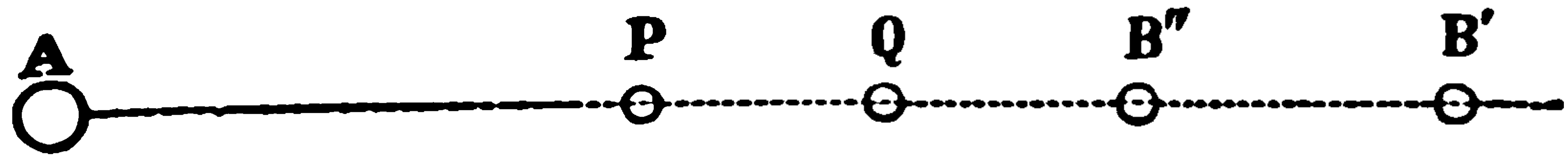


Fig. 144.

placed. Suppose the new charge thus brought near to be one + unit; when B was a long way off it would be repelled with a very slight force, and very little work need be expended in bringing it up nearer against the repelling forces exerted by A; but as B was brought nearer and nearer to A, the repelling force would grow greater and greater, and more and more work would have to be done against these opposing forces in bringing up B. Suppose that we had begun at an infinite distance away, and that we pushed up our little test charge B from B′ to B″ and then to Q, and so finally moved it up to the point P, against the opposing forces exerted by A, we

should have had to spend a certain amount of *work*; that work represents the *potential* * at the point P due to A. For the following is the *definition* of electric potential:— *The potential at any point is the work that must be spent upon a unit of positive electricity in bringing it up to that point from an infinite distance.* Had the charge on A been a – charge, the force would have been one of attraction, in which case we should have theoretically to measure the potential at P, either by the opposite process of placing there a + unit, and then removing it to an infinite distance against the attractive forces, or else by measuring the amount of work which would be *done by* a + unit in being attracted up to P from an infinite distance.

It can be shown that where there are more electrified bodies than one to be considered, the potential due to them at any point is the sum of the potentials (at that point) of each one taken separately.

It can also be shown that the potential at a point P, near an electrified particle A, is equal to the quantity of electricity at A divided hy the distance between A and P. Or, if the quantity be called q, and the distance r, the potential is $q \div r$.†

Proof.—*First determine* the difference of potential between point P and point Q due to a charge of electricity q on a small sphere at A.

Call distance AP $= r$, and AQ $= r'$. Then PQ $= r' - r$. The difference of potential between Q and P is the *work* done in moving a + unit from Q to P against the force; and since

* In its widest meaning the term "potential" must be understood as "power to do work." For if we have to do a certain quantity of work against the repelling force of a charge in bringing up a unit of electricity from an infinite distance, just so much work has the charge power to do, for it will spend an exactly equal amount of work in pushing the unit of electricity back to an infinite distance. If we lift a pound five feet high against the force of gravity, the weight of the pound can in turn do five foot-pounds of work in falling back to the ground.

† The complete proof would require an elementary application of the integral calculus, but an easy geometrical demonstration, sufficient for present purposes, is given below.

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values of r cancel out, and we get for the work done in passing from Q to P

$$V_P - V_Q = q\left(\frac{1}{r} - \frac{1}{r'}\right).$$

Next suppose Q to be an infinite distance from A. Here r' = infinity, and $\frac{1}{r'} = 0$. In that case the equation becomes

$$V_P = \frac{q}{r}.$$

If there are a number of electrified particles at different distances from P, the separate values of the potential q/r due to each electrified particle separately can be found, and therefore *the potential at P can be found by dividing the quantity of each charge by its distance from the point P, and then adding up together the separate amounts so obtained.* The symbol V is generally used to represent potential. The potential at P we will call V_P, then

$$V_P = \frac{q'}{r'} + \frac{q''}{r''} + \frac{q'''}{r'''} + \ldots \text{ etc.}$$

or $$V_P = \Sigma\frac{q}{r}.$$

This expression $\Sigma q/r$ represents the work done *on* or *by* a unit of + electricity when moved up to the given point P from an infinite distance, according as the potential at P is positive or negative.

264. Zero Potential.—At a place infinitely distant from all electrified bodies there would be no electric forces and the potential would be zero. For purposes of convenience it is, however, usual to consider the potential of the earth as an arbitrary zero, just as it is convenient to consider "sea-level" as a zero from which to measure heights or depths (see Art. 269).

265. Difference of Potentials.—Since potential represents the work that must be done on a + unit in bringing it up from an infinite distance, the *difference of*

potential between two points is *the work to be done on or by a + unit of electricity in carrying it from one point to the other*. Thus if V_P represents the potential at P, and V_Q the potential at another point Q, the difference of potentials $V_P - V_Q$ denotes the work done in moving up the + unit from Q to P. It is to be noted that since this value depends only on the values of the potential at P and at Q, and not on the values at intermediate points, the work done will be the same, whatever the path along which the particle moves from Q to P. In the same way it is true that the expenditure of energy in lifting a pound (against the earth's attraction) from one point to another on a higher level, will be the same whatever the path along which the pound is lifted.

266. **Electric Force.**—The definition of "work" is the product of the force overcome into the distance through which the force is overcome; or **work** = **force** × **distance** through which it is overcome.

Hence, if the difference of potential between two points is the work done in moving up our + unit from one point to the other, it follows that the average *electric force* between those points will be found by dividing the work so done by the distance between the points; or $\frac{V_P - V_Q}{PQ} = f$ (the average electric force along the line PQ). The (average) electric force is therefore the rate of change of potential per unit of length. If P and Q are near together the force will be practically uniform between P and Q. The term *electromotive intensity* is sometimes used for the force in an electric field.

We may represent this intensity of the electric field by supposing the number of electric lines per square centimetre to be drawn to represent the number of dynes of force on a + unit placed at the point.

267. **Equipotential Surfaces.**—A charge of electricity collected on a small sphere acts on external bodies as if the charge were all collected into one point at its

centre.* We have seen that the force exerted by such a charge falls off at a distance from the ball, the force becoming less and less as the square of the distance increases. But the force is the same in amount at all points equally distant from the small charged sphere. And the potential is the same at all points that are equally distant from the charged sphere. If, in Fig. 145, the point A represents the sphere charged with q units of

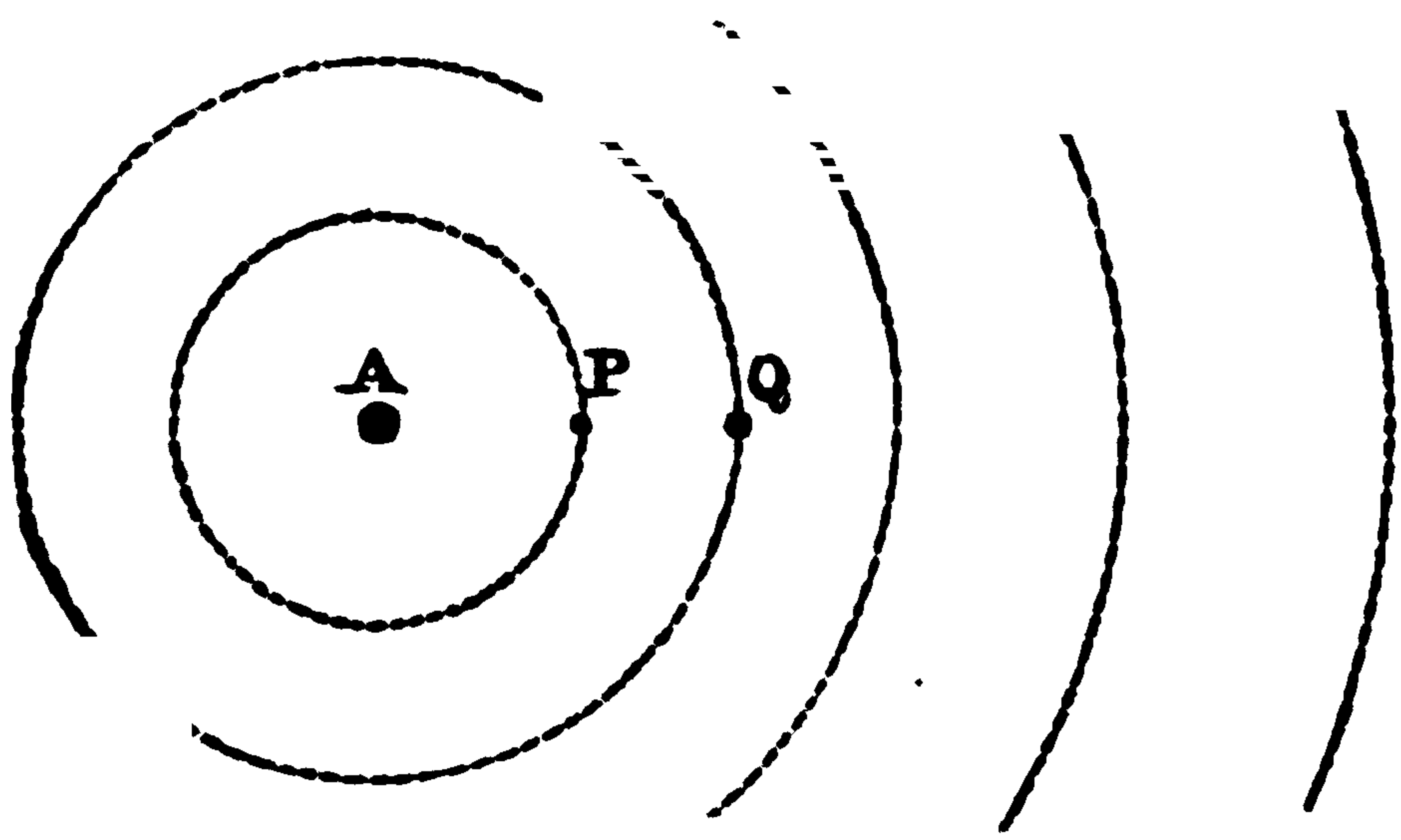


Fig. 146.

electricity, then the potential at P, which we will call V_P, will be equal to q/r, where r is the distance from A to P. But if we take any other point at the same distance from A its potential will also be q/r. Now all the points that are the same distance from A as P is, will be found to lie upon the surface of a sphere whose centre is at A, and which is represented by the circle drawn through P, in Fig. 146. All round this circle the potential will have equal values; hence this circle represents an equi-potential surface. The work to be done in bringing up a + unit from an infinite distance will be the same, no

* The student must be warned that this ceases to be true if other charges are brought very near to the sphere, for then the electricity will no longer be distributed *uniformly* over its surface. It is for this reason that we have said, in describing the measurement of electrical forces with the torsion balance, that "the balls must be very small in proportion to the distances between them."

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curved; in this case the resultant force at any point would be in the direction of the tangent to the curve at that point. Two lines of force cannot cut one another, for it is impossible; the resultant force at a point cannot act in two directions at once. The positive direction along a line of force is that direction in which a small positively-charged body would be impelled by the electric force if free to move. A space bounded by a number of lines of force is sometimes spoken of as a *tube of force.* All the space, for example, round a small insulated electrified sphere may be regarded as mapped out into a number of conical tubes, each having their apex at the centre of the sphere. The total electric force exerted across any section of a tube of force is constant wherever the section be taken.

269. Potential within a Closed Conductor.—The experiments related in Arts. 32 to 36 prove most convincingly that there is *no electric force inside a closed conductor due to charges outside or on the surface of the conductor.* Now we have shown above that electric force is the rate of change of potential per unit of length. If there is no electric force there is no change of potential. The potential within a closed conductor (for example, a hollow sphere) due to charges outside or on the surface is therefore the same all over the interior; the same as the potential of the surface. *The surface of a closed conductor is necessarily an equipotential surface.* If it were not at one potential there would be a flow of electricity from the higher potential to the lower, which would instantaneously establish equilibrium and reduce the whole to one potential. The student should clearly distinguish between the surface-density at a point, and the potential at that point due to neighbouring charges of electricity. We know that when an electrified body is placed near an insulated conductor the nearer and farther portions of that conductor exhibit induced charges of opposite kinds. Yet all is at one potential. If the +

and – charges on the conductor had not separated by a movement of electricity from one side to the other, a difference of potential would exist between those sides because they are at different distances from the electrified body. But that is a state of affairs which could not continue in the conductor, for the difference of potential would cause electricity to flow until the combined potential due to the electrified body *and the charges at the opposite sides* was the same at every point in the conductor.

The potential at any point in a conducting sphere (hollow or solid) due to an electrified particle A, situated at a point outside (Fig. 148), is equal to the quantity of electricity q at A divided by the distance between A and the centre of the sphere. For if B be the centre of the sphere, the potential at B due to q is q/r, where $r = AB$; but all points in the sphere are at the same potential, therefore they are all at the potential q/r.

The earth is a large conducting sphere. Its potential, due to a positive charge q near to its surface, is q/r, where r may be taken as the radius of the earth; that is 636,000,000 centimetres. But it is impossible to produce a + charge q without generating also an equal negative charge $-q$; so the potential of the earth due to both charges is $q/r - q/r = 0$ (see Art. 264).

270. Law of Inverse Squares.—An important consequence follows from the absence of electric force inside a closed conductor due to a charge on its surface; this fact enables us to demonstrate the necessary truth of the "law of inverse squares" which was first experimentally, though roughly, proved by Coulomb with the torsion balance. Suppose a point P anywhere inside a hollow sphere charged with electricity (Fig. 147). The charge is uniform all over, and the quantity of electricity on any small portion of its surface will be proportional to the area of that portion. Consider a small portion of the surface AB. The charge on AB would repel a + unit

placed at P with a certain force. Now draw the lines AD and BC through P, and regard these as mapping out a small conical surface of two sheets, having its apex at P; the small area CD will represent the end of the opposed cone, and the electricity on CD will also act on the + unit placed at P, and repel it. Now these surfaces AB and CD, and the charges on them, will be directly proportional to the *squares* of their respective distances from P. If, then, the forces which they exercise on P exactly neutralize one another (as experiment shows they do), it is clear that the electric force must fall off *inversely as the squares of the distances;* for the whole surface of the sphere can be mapped out similarly by imaginary cones drawn through P. The reasoning can be extended also to hollow conductors of any form.

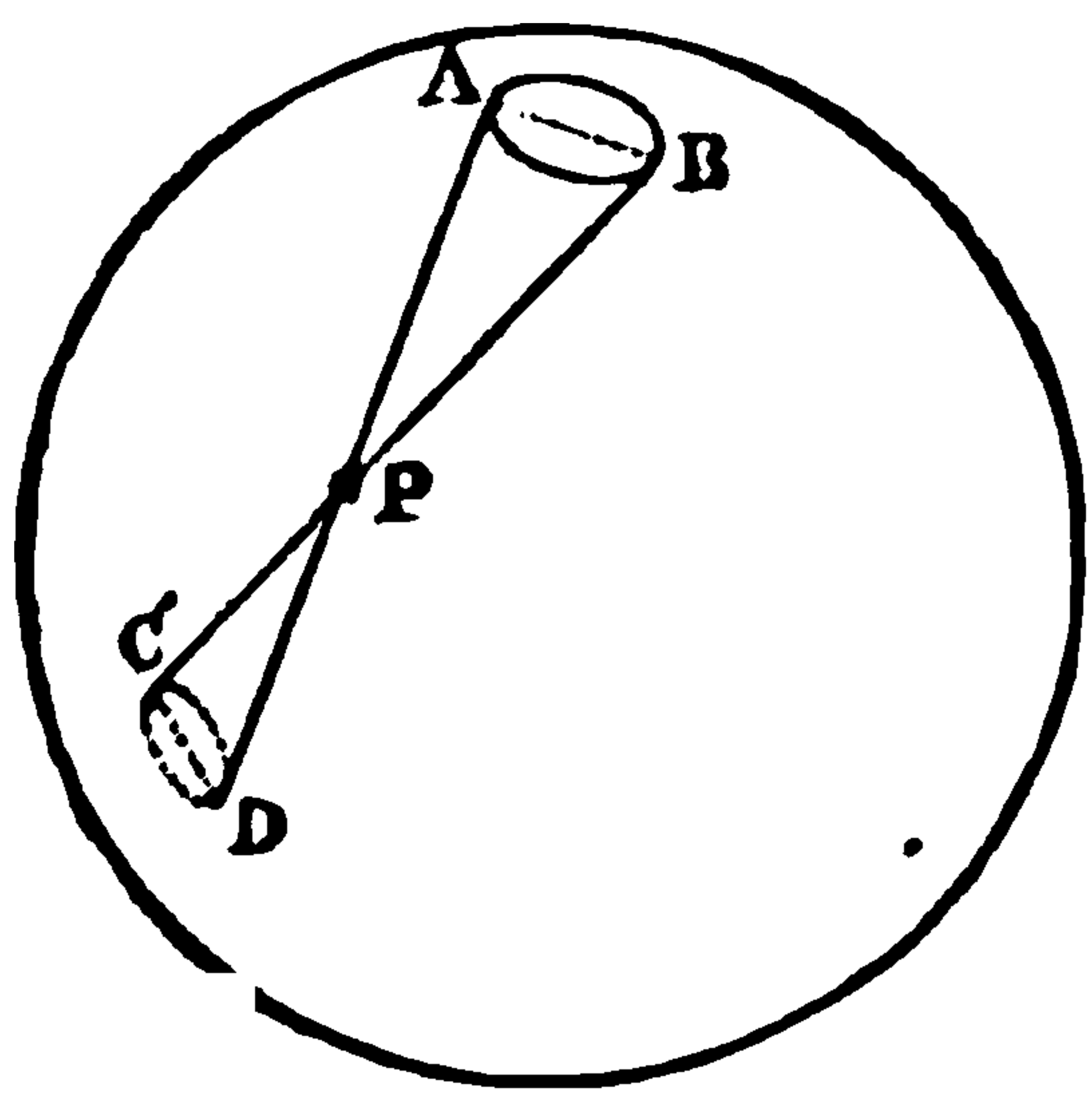


Fig. 147.

271. Capacity. — In Lesson IV. the student was given some elementary notions on the subject of the Capacity of conductors. We are now ready to give the precise definition. The Electrostatic **Capacity** of a conductor is measured by *the quantity of electricity which must be imparted to it in order to raise its potential from zero to unity.* A small conductor, such as an insulated sphere of the size of a pea, will not want so much as one unit of electricity to raise its potential from 0 to 1; it is therefore of small capacity — while a large sphere will require a large quantity to raise its potential to the same degree, and would therefore be said to be of large capacity. If K stand for capacity, and Q for a quantity of electricity,

$$K = \frac{Q}{V} \text{ and } KV = Q.$$

This is equivalent to saying in words that the quantity

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that the capacity of a sphere, as given above, means its capacity when far removed from other conductors or charges of electricity. The capacity of a conductor is increased by bringing near it a charge of an opposite kind; for the potential at the surface of the conductor is the sum of the potential due to its own charge, and of the potential of opposite sign due to the neighbouring charge. Hence, to bring up the resultant potential to unity, a larger quantity of electricity must be given to it; or, in other words, its capacity is greater. This is the true way of regarding the action of Leyden jars and other condensers, and must be remembered by the student when he advances to the consideration of the theory of condenser action, in Lesson XXIII.

273. **Surface-Density.***—Coulomb applied this term to denote the amount of electrification per unit of area at any point of a surface. It was mentioned in Lesson IV. that a charge of electricity was never distributed uniformly over a conductor, except in the case of an insulated sphere. Where the distribution is unequal, the density at any point of the surface may be expressed by considering the quantity of electricity which exists upon a small unit of area at that point. If Q be the quantity of electricity on the small surface, and S be the area of that small surface, then the surface-density (denoted by the Greek letter ρ) will be given by the equation,

$$\rho = \frac{Q}{S}.$$

* The word Tension is sometimes used for that which is here precisely defined as Coulomb defined it. The term tension is, however, unfortunate; and it is so often misapplied in text-books to mean not only surface-density but also potential, and even electric force (*i.e.* the mechanical force exerted upon a material body by electricity), that we might well avoid its use altogether. The term would be invaluable if we might adopt it to denote only the mechanical stress across a dielectric, as in Art. 279. This was Maxwell's use of the word, denoting a pulling force distributed over an area, just as the word pressure means a distributed pushing force.

In dry air, the limit to the possible electrification is reached when the density reaches the value of about 20 units of electricity per square centimetre. If charged to a higher degree than this, the electricity escapes in "sparks" and "brushes" into the air. In the case of *uniform* distribution over a surface (as with the sphere, and as approximately obtained on a flat disk by a particular device known as a guard-ring), the density is found by dividing the whole quantity of the charge by the whole surface.

274. Surface-Density on a Sphere. — The surface of a sphere whose radius is r, is $4\pi r^2$. Hence, if a charge Q be imparted to a sphere of radius r, the surface-density all over will be $\rho = \frac{Q}{4\pi r^2}$; or, if we know the surface-density, the quantity of the charge will be $Q = 4\pi r^2 \rho$.

The surface-density on *two spheres* joined by a thin wire is an important case. If the spheres are unequal, they will share the charge in proportion to their capacities (see Art. 40), that is, in proportion to their radii. If the spheres are of radii 2 and 1, the ratio of their charges will also be as 2 to 1. But their respective densities will be found by dividing the quantities of electricity on each by their respective surfaces. But the surfaces are proportional to the squares of the radii, *i.e.* as 4 : 1; hence, the densities will be as 1 : 2, or *inversely as the radii.* Now, if one of these spheres be very small — no bigger than a point — the density on it will be relatively immensely great, so great that the air particles in contact with it will rapidly carry off the charge by convexion. This explains the *action of* points in discharging conductors, noticed in Chapter I., Arts. 38, 45, and 47.

275. Electric Images — It can be shown mathematically that if $+ q$ units of electricity are placed at a point near a non-insulated conducting sphere of radius

r, at a distance d from its centre, the negative induced charge will be equal to $-qr/d$, and will be distributed over the nearest part of the surface of the sphere with a surface-density inversely proportional to the cube of the distance from that point. Lord Kelvin pointed out that, so far as all external points are concerned, the potential due to this peculiar distribution on the surface would be exactly the same as if this negative charge were all collected at an internal point at a distance of $r - r^2/d$ behind the surface. Such a point may be regarded as a *virtual image* of the external point, in the same way as in optics we regard certain points behind mirrors as the virtual images of the external points from which the rays proceed. Clerk Maxwell has given the following definition of an Electric Image:—*An electric image is an electrified point, or system of points, on one side of a surface, which would produce on the other side of that surface the same electrical action which the actual electrification of that surface really does produce.* If the sphere is not connected to earth, and were unelectrified before $+q$ was brought near it, we may find the surface-density at any point by the following convention. Imagine that there are coexisting on the sphere two charges, $-rq/d$ and $+rq/d$ respectively, the first being distributed so that its surface-density is inversely proportional to the cube of the distance from the electrified point, and the second being uniformly distributed. The actual surface-density is the algebraic sum of these two. A + charge of electricity placed 1 inch in front of a flat metallic plate induces on it a negative charge distributed over the neighbouring region of the plate (with a density varying inversely as the cube of the distance from the point); but the electrical action of this distribution, so far as all points in front of the plate are concerned, would be precisely represented by its "image," namely, by an equal quantity of negative electricity placed at a point 1 inch *behind* the plate. Many beautiful mathematical applications of this

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faces. These two propositions are of the utmost importance in the theory of Electrostatics.

278. Proof of Theorem. — The elementary geometrical proof is as follows: —

Required the Electric Force at point at any distance from a plane of infinite extent charged to surface-density ρ.

Let P be the point, and PX or a the normal to the plane. Take any *small* cone having its apex at P. Let the solid angle of this cone be ω; let its length be r; and θ the angle its axis

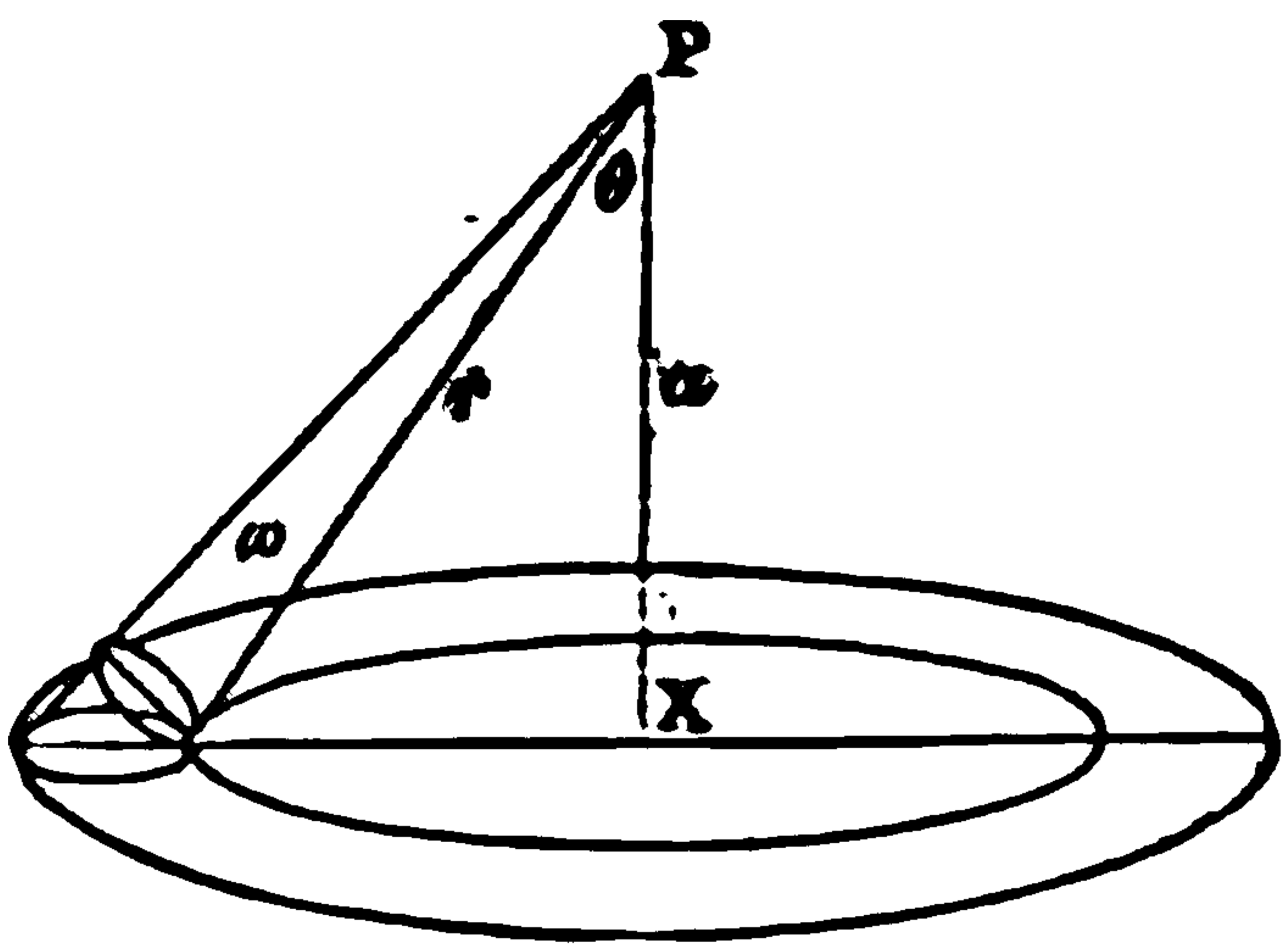


Fig. 149.

makes with a. The cone meets the surface of the plane obliquely, and if an orthogonal section be made where it meets the plane, the angle between these sections will be $= \theta$.

Now solid angle ω is by definition $= \dfrac{\text{orthogonal area of section}}{r^2}$.

Hence, area of oblique section $= r^2\omega \times \dfrac{1}{\cos\theta}$;

$\therefore$ charge on oblique section $= \dfrac{r^2\omega\rho}{\cos\theta}$.

Hence if a + unit of electricity were placed at P, the force exerted on this by this small change $= \dfrac{r^2\omega\rho}{\cos\theta} \times 1 \div r^2$,

or $$= \frac{\omega\rho}{\cos\theta}.$$

Resolve this force into two parts, one acting along the plane, the other along a, normal to the plane. The normal component along a is $\cos\theta \times \dfrac{\omega\rho}{\cos\theta} = \omega\rho$.

But the whole surface of the plane may be similarly mapped out into small surfaces, all forming small cones, with their summits at P. If we take an infinite number of such small cones meeting every part, and resolve their forces in a similar way, we shall find that the components along the plane will neutralize one another all round, while the normal components, or the resolved forces along a, will be equal to the sum of all their solid angles multiplied by the surface-density; or

$$\text{Total resultant force along } a = \Sigma\omega\rho.$$

But the total solid angle subtended by an indefinite plane at a point is 2π, for it subtends a whole hemisphere.

$$\therefore \text{Total resultant force} = 2\pi\rho.$$

279. Electric Stress in Medium. — In every electric field (Art. 13) there exists a *tension* along the lines of electric force accompanied by an equal *pressure* in all directions at right angles to the lines. If F stands for the resultant electric force on a + unit placed at any point in the field (*i.e.* the "electromotive intensity" at that point), the tension will be equal to $F^2/8\pi$ (dynes per square centimetre). In media having dielectric capacities greater than unity the tension is proportionately greater. For the optical effects of these stresses see Art. 525.

NOTE ON FUNDAMENTAL AND DERIVED UNITS

280. Fundamental Units. — All physical qualities, such as force, velocity, etc., can be expressed in terms of the three fundamental quantities: *length*, *mass*, and *time*. Each of these quantities must be measured in terms of its own units.

The system of units, adopted by almost universal consent, and used throughout these lessons, is the so-called "Centimetre-Gramme-Second" system, in which the fundamental units are: —

The *Centimetre* as a unit of *length*;
The *Gramme* as a unit of *mass*;
The *Second* as a unit of *time*.

The *Centimetre* is equal to 0·3937 inch in length, and nomi-

nally represents one thousand-millionth part, or $\frac{1}{1,000,000,000}$ of a quadrant of the earth.

The *Metre* is 100 centimetres, or 39·37 inches.

The *Kilometre* is 1000 metres, or about 1093·6 yards.

The *Millimetre* is $\frac{1}{10}$ of a centimetre, or 0·03937 inch.

The *Gramme* represents the mass of a cubic centimetre of water at 4° C., this is equal to 15·432 grains: the *Kilogramme* is 1000 grammes or about 2·2 pounds.

281. Derived Units.—

Area.—The unit of area is the *square centimetre.*

Volume.—The unit of volume is the *cubic centimetre.*

Velocity.—The unit of velocity is the velocity of a body which moves through unit distance in unit time, or the *velocity of one centimetre per second.*

Acceleration.—The unit of acceleration is that acceleration which imparts unit velocity to a body in unit time, or an acceleration of one centimetre-per-second per second. The acceleration due to gravity imparts in one second a velocity considerably greater than this, for the velocity it imparts to falling bodies is about 981 centimetres per second (or about 32·2 feet per second). The value differs slightly in different latitudes. At Greenwich the value of the acceleration of gravity is $g = 981 \cdot 1$; at the Equator $g = 978 \cdot 1$; at the North Pole $g = 983 \cdot 1$.

Force.—The unit of force is that force which, acting for one second on a mass of one gramme, gives to it a velocity of one centimetre per second. It is called one *Dyne.* The force with which the earth attracts any mass is usually called the "weight" of that mass, and its value obviously differs at different points of the earth's surface. The force with which a body gravitates, *i.e.* its weight (in dynes), is found by multiplying its mass (in grammes) by the value of g at the particular place where the force is exerted. One pound force in England is about 445,000 dynes.

Work.—The unit of work is the work done in overcoming unit force through unit distance, *i.e.* in pushing a body through a distance of one centimetre against a force of one dyne. It is called one *Erg.* Since the "weight" of one gramme is 1×981 or 981 dynes, the work of raising one gramme through the height of one centimetre against the force of gravity is 981 ergs.

Energy.—The unit of energy is also the *erg;* for the energy of a body is measured by the work it can do.

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is, in the absence of any knowledge of its absolute value, taken as unity.

Electromotive Intensity is the electric force or intensity of an electric field at any point, and is measured by the force which it exerts on a unit charge placed at that point.

It may be convenient here to append the rules for reducing to their corresponding values in terms of the practical (electro-magnetic) units values that may have been expressed in terms of the electrostatic units, as follows: —

Potential. To bring to *volts* multiply by 300.
Capacity. To bring to *microfarads* divide by 900,000.
Quantity. To bring to *coulombs* divide by 3×10^9.
Current. To bring to *amperes* divide by 3×10^9.
Resistance. To bring to *ohms* multiply by 9×10^{11}.

Example. — Suppose two equally charged spheres whose centres are 40 centimetres apart are found to repel one another with a force of 630 dynes (= about the weight of 10 grains). By the law of inverse squares we find that the charge on each is 1004 (electrostatic units. Dividing by 3×10^9 we find that this amounts to 0·0000003347 *coulomb*.

284. **Dimensions of Units.** — It has been assumed above that a velocity can be expressed in centimetres per second; for velocity is rate of change of place, and it is clear that if change of place may be measured as a length in centimetres, the *rate* of change of place will be measured by the number of centimetres through which the body moves in unit of time. It is impossible, indeed, to express a velocity without regarding it as the quotient of a certain number of units of length divided by a certain number of units of time. In other words, a velocity $= \frac{\text{a length}}{\text{a time}}$; or, adopting L as a symbol for length, and T as a symbol for time, $V = \frac{L}{T}$, which is still more conveniently written $V = L \times T^{-1}$. In a similar way *acceleration* being rate of change of velocity, we have $A = \frac{V}{T} = \frac{L}{T \times T} = \frac{L}{T^2} = L \times T^{-2}$.

Now these physical quantities, "velocity" and "acceleration," are respectively *always* quantities of the same nature, no matter whether the centimetre, or the inch, or the mile, be taken as the unit of length, or the second or any other interval be taken as the unit of time. Hence we say that these abstract equations express the *dimensions* of those quantities with respect to the fundamental quantities length and time. A little consideration

will show the student that the dimensions of the various units mentioned above will therefore be as given in the table below.

The dimensions of magnetic units are given in the Table in Art. 356, p. 348.

TABLE OF DIMENSIONS OF UNITS.

	UNITS.				DIMENSIONS.
	(Fundamental)				
l	Length				L
m	Mass				M
t	Time				T
	(Derived)				
	Area	=	$L \times L$	=	L^2
	Volume	=	$L \times L \times L$	=	L^3
v	Velocity	=	$L \div T$	=	LT^{-1}
a	Acceleration	=	velocity ÷ time	=	LT^{-2}
f	Force	=	mass × acceleration	=	MLT^{-2}
	Work	=	force × length	=	ML^2T^{-2}
	(Electrostatic)				
q	Quantity	=	$\sqrt{\text{force} \times (\text{distance})^2}$	=	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-1}$
i	Current	=	quantity ÷ time	=	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-2}$
V	Potential	=	work ÷ quantity	=	$M^{\frac{1}{2}} L^{\frac{1}{2}} T^{-1}$
R	Resistance	=	potential ÷ current	=	$L^{-1} T^1$
C	Capacity	=	quantity ÷ potential	=	L
k	Sp. Ind. Capacity	=	quantity ÷ another quantity		a numeral
F	Electromotive Intensity	=	force ÷ quantity	=	$M^{\frac{1}{2}} L^{\frac{1}{2}} T^{-1}$

LESSON XXII. — *Electrometers*

285. In Lesson II. we described a number of *electroscopes* or instruments for indicating the presence and sign of a charge of electricity; some of these also served

to indicate roughly the amount of these charges, but none of them save the torsion balance could be regarded as affording an accurate means of measuring either the *quantity* or the *potential* of a given charge. *An instrument for measuring differences of electrostatic potential is termed an* **Electrometer.** Such instruments can also be used to measure electric *quantity* indirectly, for the quantity of a charge can be ascertained by measuring the potential to which it can raise a conductor of known capacity. The earliest electrometers attempted to measure the quantities directly. Lane and Snow Harris constructed "Unit Jars" or small Leyden jars, which, in order to measure out a certain quantity of electricity, were charged and discharged a certain number of times.

286. Repulsion Electrometers. — The torsion balance, described in Art. 18, measures quantities by measuring the forces exerted by the charges given to the fixed and movable balls. It can only be applied to the measurement of repelling forces, for the equilibrium is unstable in the case of a force of attraction.

Beside the gold-leaf electroscope and others described in Lesson II., there exist several finer electrometers based upon the principle of repulsion, some of which resemble the torsion balance in having a movable arm turning about a central axis. Amongst these are the electrometers of Dellmann and of Peltier. In the latter a light arm of aluminium, balanced upon a point, carries also a small magnet to direct it in the magnetic meridian. A fixed arm, in metallic contact with the movable one, also lies in the magnetic meridian. A charge imparted to this instrument produces a repulsion between the fixed and movable arms, causing an angular deviation. Here, however, the force is measured not by being pitted against the torsion of an elastic fibre, or against gravitation, but against the directive magnetic force of the earth acting on the small needle. Now this depends on the intensity

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description of all the various forms of attracted-disk electrometer;* but the main principles of them all can be readily explained.

The disk C, whose attraction is to be measured, is suspended (Fig. 150) within a fixed guard-plate B, which surrounds it without touching it, and which is placed in metallic contact with it by a fine wire. A Lever L supports the disk, and is furnished with a counterpoise. In order to know whether the disk is precisely level with the lower surface of the guard-plate a little gauge or index

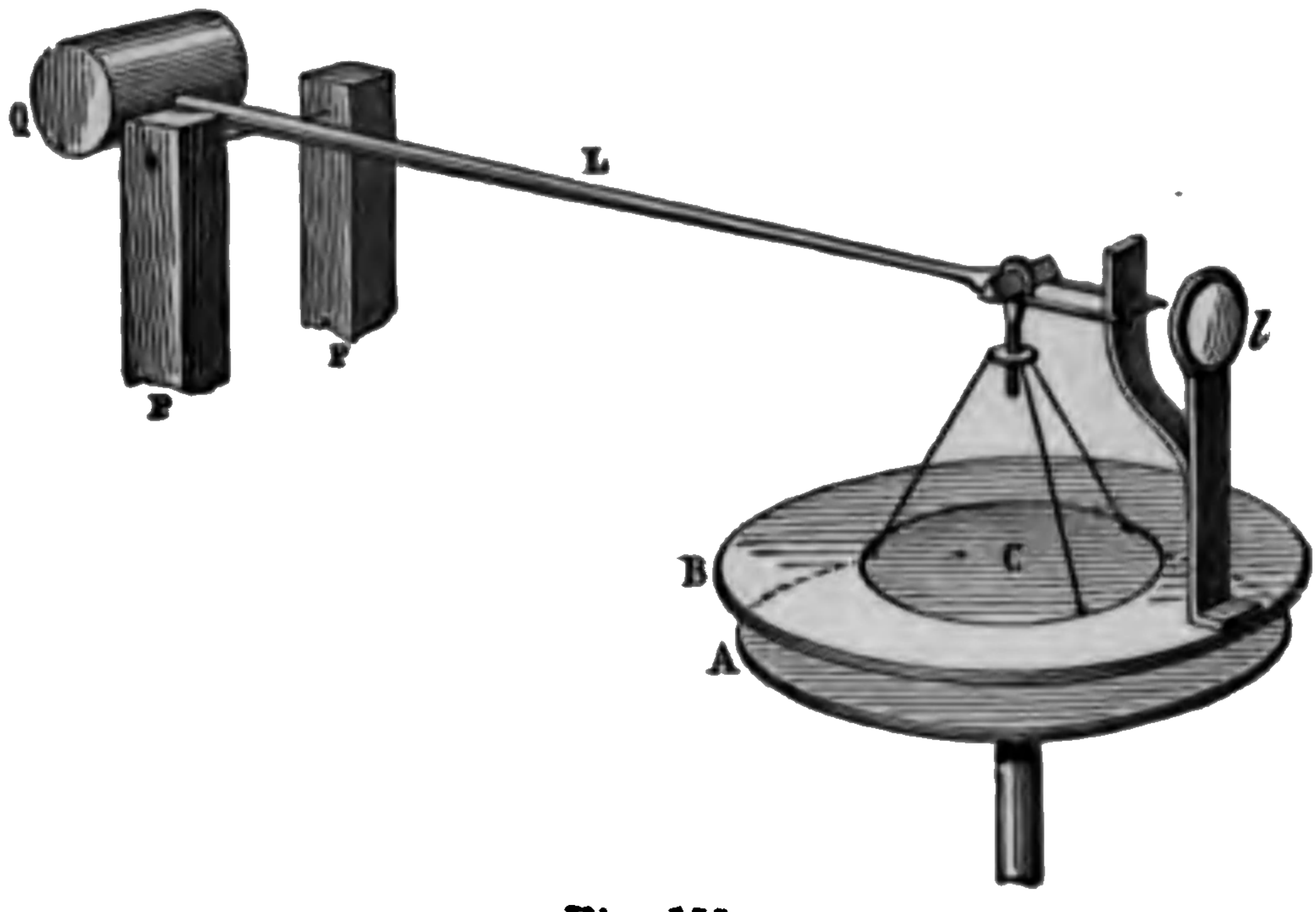


Fig. 150.

is fixed above, and provided with a lens *l* to observe its indications. Beneath the disk and guard-plate is a second disk A, supported on an insulating stand. This lower disk can be raised or lowered at will by a micrometer screw, great care being taken in the mechanical arrangements that it shall always be parallel to the plane of the guard-plate. Now, since the disk and guard-plate are in metallic connexion with one another, they form virtually part of one surface, and as the irregularities of distribution

* For these the student is referred to the volume of Lord Kelvin's papers, "On Electrostatics and Magnetism"; or to Professor Andrew Gray's *Absolute Measurements in Electricity and Magnetism*.

occur at the edges of the surface, the distribution over the area of the disk is practically uniform. Any attraction of the lower plate upon the disk *might* be balanced either by increasing the weight of the counterpoise, or by putting a torsion on the aluminium wire which serves as a fulcrum; but in practice it is found most convenient to obtain a balance by altering the distance of the lower plate until the electric force of attraction exactly balances the forces (whether of torsion or of gravity acting on the counterpoise) which tend to lift the disk above the level of the guard-plate.

The theory of the instrument is simple also. Let V_1 represent the potential of the movable disk, which has a positive charge of surface-density ρ, and let V_2 be the potential of the fixed plate, upon which is a charge of surface-density $-\rho$. The difference of potential $V_1 - V_2$ is the work which would have to be done upon a unit of positive charge in taking it from V_2 to V_1. Now the force upon such a unit placed between the two plates would be (an attraction of $2\pi\rho$ due to the fixed plate, and a repulsion of $2\pi\rho$ due to the movable plate, see Art. 278) altogether $4\pi\rho$, and if the distance between the plates were D. Work = force × distance.

$$V_1 - V_2 = 4\pi\rho D.$$

If S is the area of the movable plate, $S\rho$ is the total quantity of electricity on it; therefore it would be attracted by the fixed plate with a force $F = 2\pi\rho \times S\rho$. From this we get

$$\rho = \sqrt{\frac{F}{2\pi S}}.$$

Substituting this value of ρ in the above equation, we get

$$V_1 - V_2 = D\sqrt{\frac{8\pi F}{S}}.$$

If F is measured in dynes, S in square centimetres, and D in centimetres, the potentials will be in absolute electro-

static units, and must be multiplied by 300 to bring to *volts* (see Art. 283).

From this we gather that, if the force F remains the same throughout the experiments, *the difference of potentials between the disks will be simply proportional to the distance between them* when the disk is in level equilibrium. And the quantity $\sqrt{\frac{8\pi F}{S}}$ may be determined once for all as a "constant" of the instrument.

In the more elaborate forms of the instrument, such as the "absolute electrometer," and the "portable electrometer," the disk and guard-plate are covered with a metallic cage, and are together placed in communication with a condenser to keep them at a known potential. This obviates having to make measurements with zero readings, for the *differences of potential* will now be proportional to *differences of micrometer readings*,

or, $$V_1 - V_2 = (D_1 - D_2)\sqrt{\frac{8\pi F}{S}}.$$

The condenser is provided in these instruments with a *gauge*, itself an attracted disk, to indicate when it is charged to the right potential, and with a *replenisher* to increase or decrease the charge, the replenisher being a little influence machine (see Art. 50).

288. The Quadrant Electrometer. — The Quadrant Electrometer of Sir W. Thomson is an example of a different class of electrometers, in which use is made of an auxiliary charge of electricity previously imparted to the needle of the instrument. The needle, which consists of a thin flat piece of aluminium hung horizontally by a fibre of thin wire, thus charged, say positively, will be attracted by a − charge, but repelled by a + charge. Such attraction or repulsion will be stronger in proportion to these charges, and in proportion to the charge on the needle. Four quadrant-pieces (Fig. 151) of brass are fixed

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telescope sees an image of the zero of the scale reflected in the little mirror. The wires connecting quadrants 1 and 3, 2 and 4, are seen above the top of the case.

For very exact measurements many additional refinements are introduced into the instrument. Two sets of quadrants are employed, an upper and a lower, having the needle between them. The torsion wire is replaced by a delicate bifilar suspension (Art. 130). To keep up the charge of the Leyden jar a "replenisher" is added; and an "attracted-disk," like that of the Absolute Electrometer, is employed in order to act as a gauge to indicate when the jar is charged to the right potential. In these forms the jar consists of a glass vessel placed below the quadrants, coated externally with strips of tinfoil, and containing strong sulphuric acid, which serves the double function of

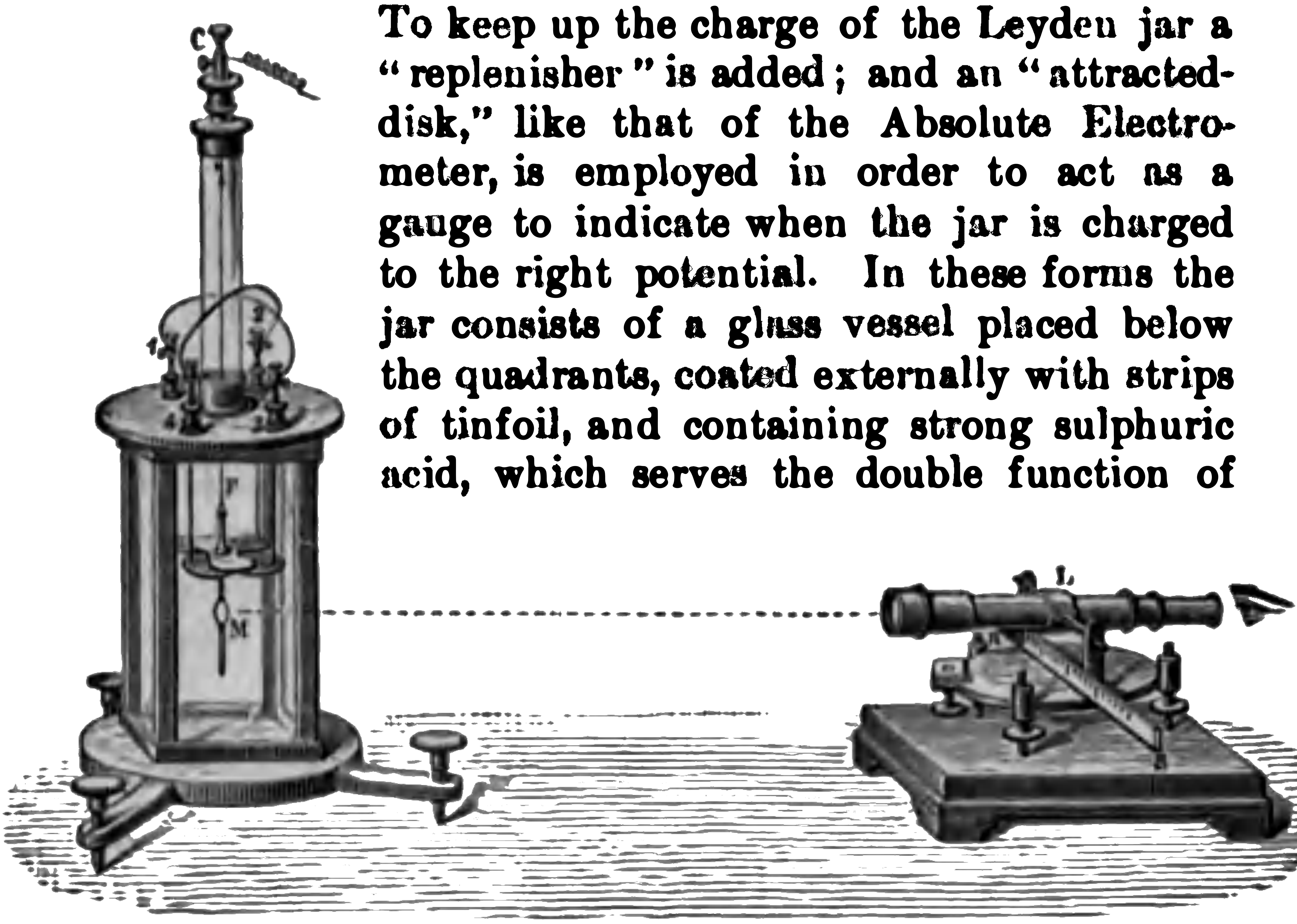


Fig. 152.

keeping the apparatus dry by absorbing the moisture and of acting as an internal coating for the jar. It is also more usual to throw a spot of light from a lamp upon a scale by means of the little mirror (as described in the case of the Mirror Galvanometer, in Art. 215), than to adopt the subjective method with the telescope, which only one person at a time can use. When the instrument is provided with replenisher and gauge, the measurements

can be made in terms of absolute units, provided the "constant" of the particular instrument (depending on the suspension of the needle, size and position of needle and quadrants, potential of the gauge, etc.) is once ascertained.

289. Use of Quadrant Electrometer. — An example will illustrate the mode of using the instrument. It is known that when the two ends of a thin wire are kept at two different potentials a current flows through the wire, and that if the potential is measured at different points along the wire, it is found to fall off in a perfectly uniform manner from the end that is at a high potential down to that at the low potential. At a point one quarter along the potential will have fallen off one quarter of the whole difference. This could be proved by joining the two ends of the wire through which the current was flowing to the terminals of the Quadrant Electrometer, when one pair of quadrants would be at the high potential and the other at the low potential. The needle would turn and indicate a certain deflexion. Now, disconnect one of the pairs of quadrants from the low potential end of the wire, and place them in communication with a point one quarter along the wire from the high potential end. The needle will at once indicate that the difference of potential is but one quarter of what it was before.

Often the Quadrant Electrometer is employed simply as a very delicate electro*scope* in systems of measurement in which a difference of electric potential is measured by being balanced against an equal and opposite difference of potential, exact balance being indicated by there being *no* deflexion of the Electrometer needle. Such methods of experimenting are known as *Null Methods*, or *Zero Methods*.

290. Electrostatic Voltmeter. — We have seen that in the quadrant electrometer it is necessary to give the needle a high initial charge, the reason being that if there did not exist between the quadrants and the needle a much greater difference of potential than the small voltage we are measuring, the force tending to turn the needle would be too small to be conveniently observed. Where, however, we are dealing with high differences of potential a separately-charged needle is not requisite; we may simply join one conductor to the needle and the other to a set of quadrants, and the force of

attraction, which, other things being equal, increases as the square of the difference of potential, is sufficiently great to give reliable readings. This is known as the *idiostatic* method of using the instrument.

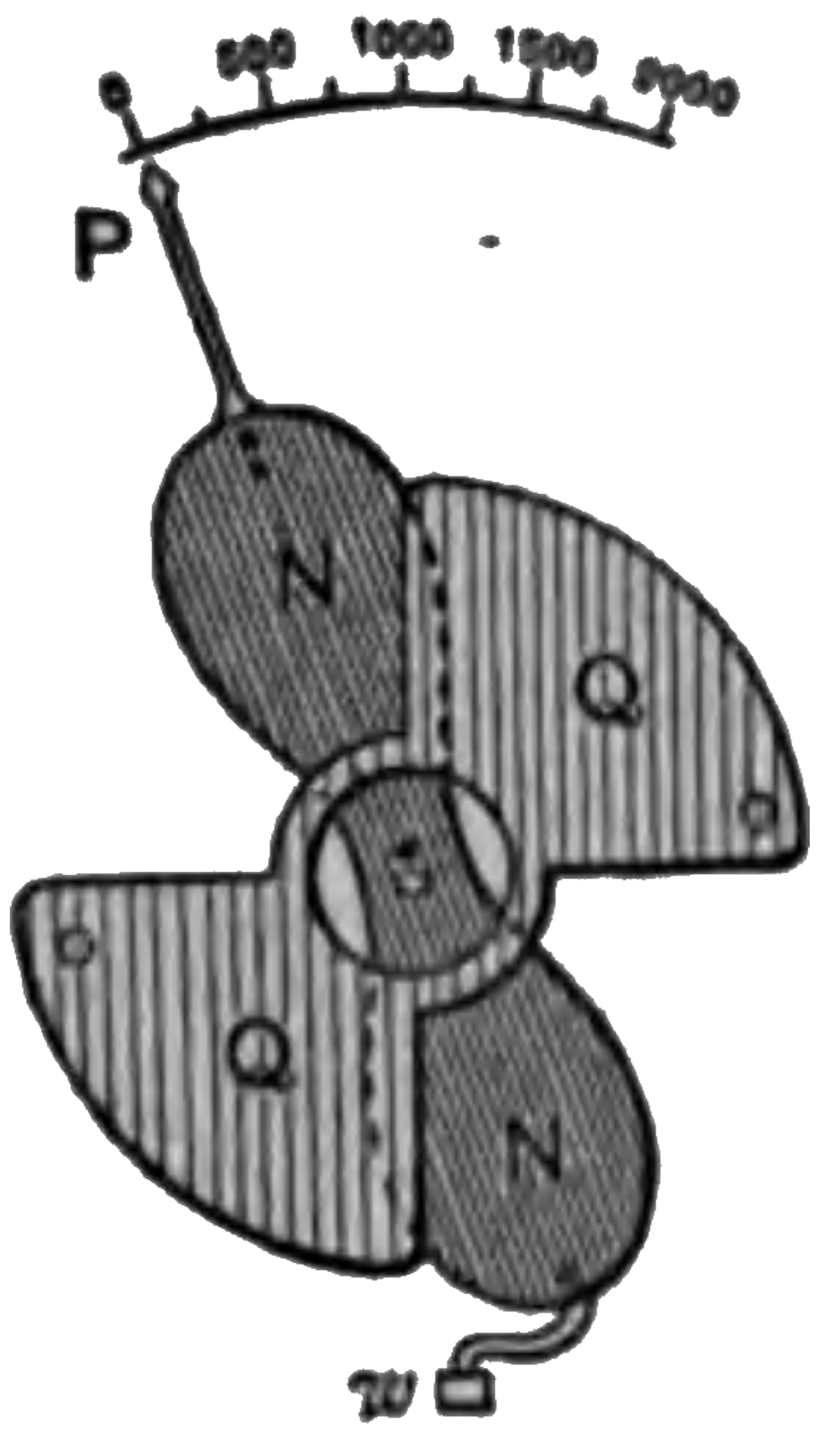


Fig. 153.

A front view of the instrument as commonly used to measure differences of potential of 1000 volts or more, is shown in Fig. 153. The needle NN is a paddle-shaped plate of aluminium supported by knife edges at its centre; its position is controlled by gravity, little weights being hung on a projection at its lower end. The quadrants Q are both behind and in front of it, and so placed that when a difference of potential exists between the needle and them the needle is deflected from its normal position and moves its pointer over a graduated scale.

It will be seen that it does not matter whether the needle is positively charged and the quadrants negatively charged or *vice versâ*; an attraction between the two will always take place, so a deflexion will be given even when the difference of potential is rapidly alternating. This property of the instrument makes it exceedingly useful for the measurement of voltage when alternating currents are used.

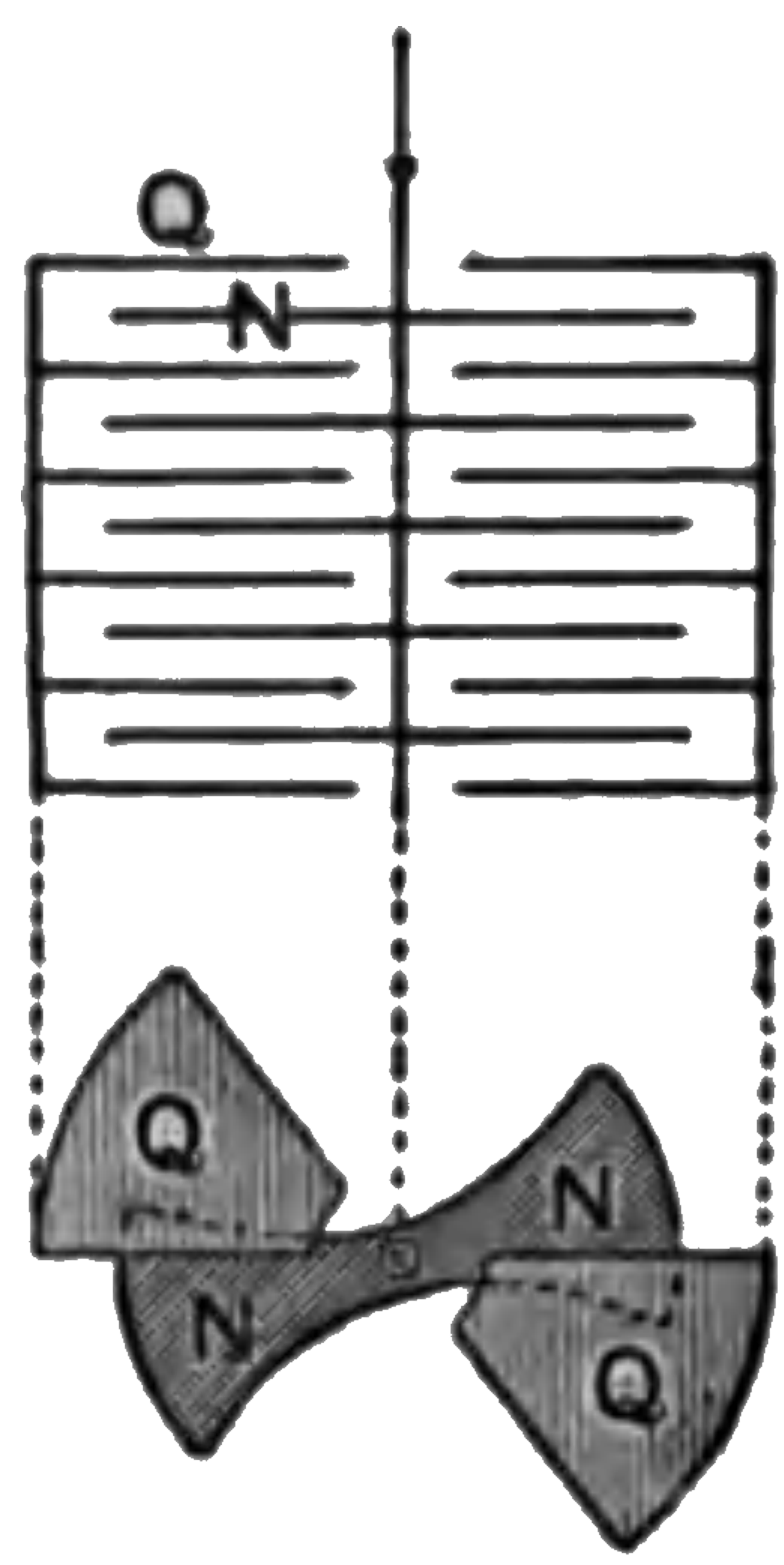


Fig. 154.

Another advantage of this instrument over the high-resistance galvanometers that are used as voltmeters is, that it does not take any current, and consequently it does not waste any power.

In order to make the electrostatic voltmeter sufficiently delicate to measure down to 100 volts or so, a number of

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by air. The inner one, A, will represent the interior coating of tinfoil, and the outer sphere, B (Fig. 155), will represent the exterior coating. Let the radii of these spheres be r and r' respectively. Suppose a charge of Q units to be imparted to A; it will induce on the inner side of B an equal negative charge $-$ Q, and to the outer side of B a charge + Q will be repelled. This latter is removed by contact with "earth," and need be no further considered. The potential * at the centre M, calculated by the rule given in Art. 263, will be

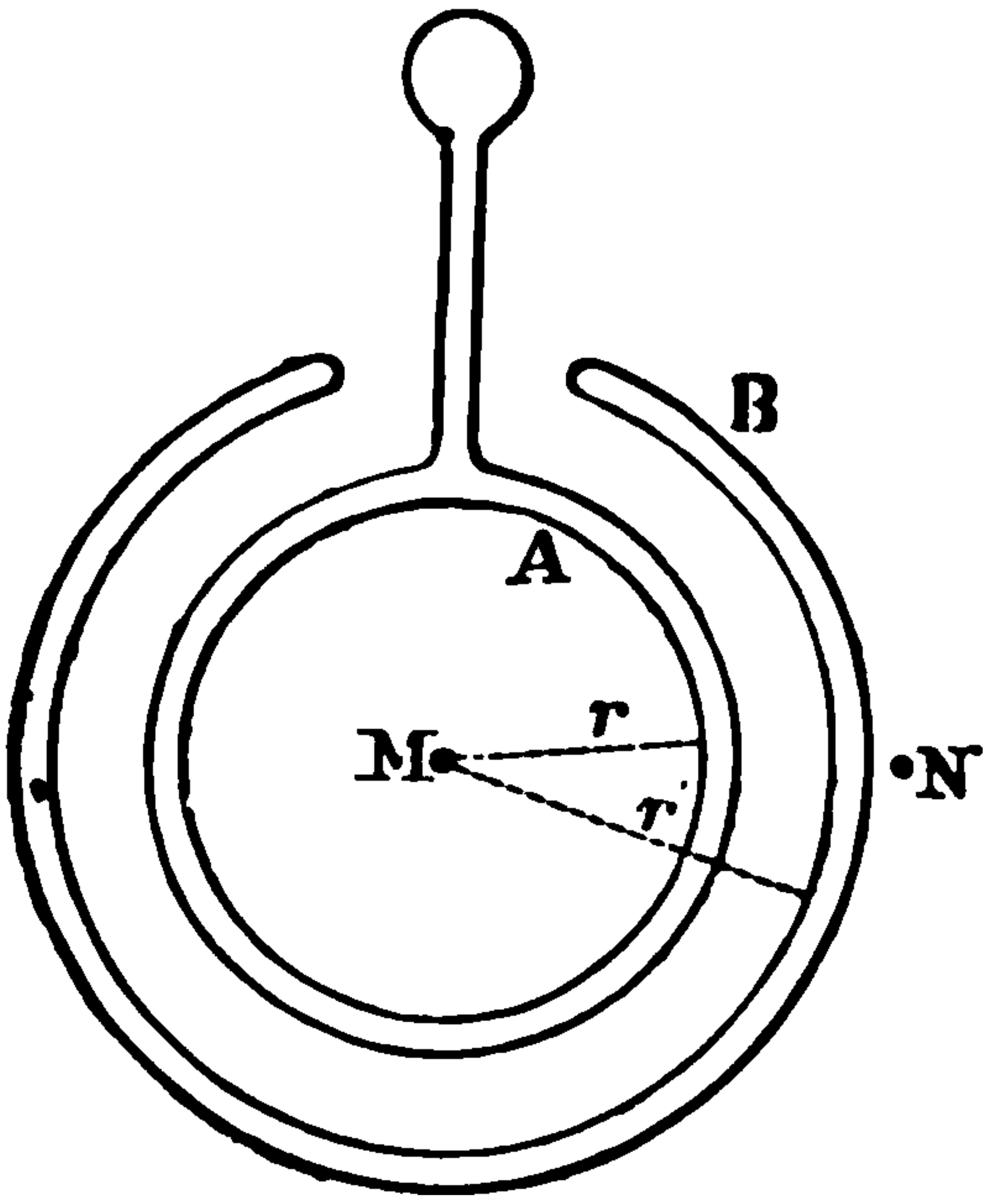


Fig. 155.

$$V_M = \frac{Q}{r} - \frac{Q}{r'}.$$

At a point N, outside the outer sphere and quite near to it, the potential will be the same as if these two charges, + Q and $-$ Q, were both concentrated at M. Hence

$$V_N = \frac{+Q - Q}{r'} = 0.$$

So then the difference of potentials will be

$$V_M - V_N = \frac{Q}{r} - \frac{Q}{r'} = Q\left(\frac{r' - r}{rr'}\right);$$

whence $$\frac{Q}{V_M - V_N} = \frac{rr'}{r' - r}.$$

But by Art. 270 the capacity $K = \dfrac{Q}{V_M - V_N}$,

therefore $$K = \frac{rr'}{r' - r}.$$

* The student must remember that as there is no electric force within a closed conductor, the potential at the middle is just the same as at any other point inside.

We see from this formula that the capacity of the condenser is proportional to the size of the metal globes, and that if the insulating layer is very thin, — that is, if r be very nearly as great as r', $r' - r$ will become very small, and the value of the expression $\frac{rr'}{r' - r}$ will become very great; which proves the statement that the capacity of a condenser depends upon the *thinness* of the layer of dielectric. If r' is very great compared with r, the expression for the capacity becomes equal simply to r, that of the inner sphere when isolated.

295. Specific Inductive Capacity. — Cavendish was the first to discover that the capacity of a condenser depended not on its actual dimensions only, but upon the *inductive power* of the material used as the dielectric between the two surfaces. If two condensers (of any of the forms to be described) are made of exactly the same size, and in one of them the dielectric be a layer of air, and in the other a layer of some other insulating substance, it is found that equal quantities of electricity imparted to them do not produce equal differences of potentials; or, in other words, it is found that they have not the same capacity. If the dielectric be mica, for example, it is found that the capacity is about six times as great; for mica possesses a high inductive power and allows the transmission across it of electrostatic influence six times as well as air does. The name **specific inductive capacity,*** or **dielectric capacity,** is given to the ratio between the capacities of two condensers equal in size, one of them being an air condenser, the other filled with the specified dielectric. The specific inductive capacity of dry air at the temperature 0° C., and pressure 76 centimetres, is taken as the standard, and, in the absence of any known way of finding its absolute value, is reckoned

* The name is not a very happy one, — *inductivity* would have been better, and is the analogous term, for dielectrics, to the term "conductivity" used for conductors. The term *dielectric coefficient* is also used by some modern writers.

as unity. The symbol k is used to denote the dielectric capacity of any material.

Cavendish, about the year 1775, measured the dielectric capacity of glass, bees-wax, and other substances, by forming them into condensers between two circular metal plates, the capacity of these condensers being compared with that of an air condenser (resembling Fig. 42) and with other condensers which he called "trial-plates." He even went so far as to compare the capacities of these "trial-plates" with that of an isolated sphere of 12⅓ inches diameter hung up in a room.



Fig. 156.

296. Faraday's Experiments. — In 1837 Faraday, who did not know of the then unpublished researches of Cavendish, independently discovered specific inductive capacity, and measured its value for several substances, using for this purpose two condensers of the form shown in Fig. 156. Each consisted of a brass ball A, enclosed inside a hollow sphere of brass B, and insulated by a long plug of shellac, up which passed a wire terminating in a knob *a*. The outer sphere consisted of two parts which could be separated from each other in order to fill the hollow space with any desired material: the experimental process then was to compare their capacities when one was filled with the substance to be examined, the other containing only dry air. One of the condensers was charged with electricity. It was then made to share its

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quadrant electrometer that when the capacities of the separate parts are adjusted to equality there shall be no deflexion in the electrometer, whatever be the amount or sign of the electrification at the moment. This arrangement, when employed in conjunction with an induction coil (Fig. 135) and a rapid commutator, admits of the inductive capacity being measured when the duration of the actual charge is only very small, the electrification being reversed 12,000 times per second. Such an instrument, therefore, overcomes one great difficulty besetting these measurements, namely, that owing to the apparent absorption of part of the charge by the dielectric (as mentioned in Art. 61), the capacity of the substance, when measured slowly, is different from its "instantaneous capacity." This electric absorption is discussed further in Art. 299. For this reason the values assigned by different observers for the dielectric capacity of various substances differ to a most perplexing degree, especially in the case of the less perfect insulators. The following table summarizes Gordon's observations:—

Air	1·00
Glass	3·013 to 3·258
Ebonite	2·284
Guttapercha	2·462
Indiarubber	2·220 to 2·497
Paraffin (solid)	1·9936
Shellac	2·74
Sulphur	2·58

Hopkinson, whose method was a "slow" one, found for glass much higher inductive capacities, ranging from 6·5 to 10·1, the denser kinds having higher capacities. Mica has values ranging from 5·5 to 8. Cavendish observed that the apparent capacity of glass became much greater at those temperatures at which it begins to conduct electricity. Boltzmann has announced that in the case of two crystalline substances, Iceland spar and sulphur, the inductive capacity is different in different

directions, according to their position with respect to the axes of crystallization.

298. Dielectric Capacity of Liquids and Gases. — The dielectric capacity of liquids also has specific values, as follows: —

Turpentine	2·16
Petroleum	2·03 to 2·07
Bisulphide of Carbon . . .	1·81

Faraday examined the inductive capacity of several gases by means of his apparatus (Fig. 156), one of the condensers being filled with air, the other with the gas which was let in through the tap below the sphere after exhaustion by an air pump. The method was too rough, however, to enable him to detect any difference between them. More recently Boltzmann, and independently Ayrton and Perry, have measured the dielectric capacities of different gases by very exact methods; and their results agree very fairly.

	Boltzmann.	Ayrton and Perry.
Air	(1)	(1)
Vacuum	(0·999410)	(0·9985)
Hydrogen	0·999674	0·9998
Carbonic Acid . . .	1·000356	1·0008
Olefiant Gas . . .	1·000722	
Sulphur Dioxide . .		1·0037

The effect of using instead of air a medium of higher dielectric power k is to change the forces exerted between charged bodies. For given fixed charges the forces vary *inversely* as k; while for given differences of potential between the bodies the forces vary directly as k.

299. Mechanical Effects of Dielectric Stress. — That different insulating substances have specific inductive power sufficiently disproves the idea that influence is

merely an "action at a distance," for it is evident that the dielectric medium is itself concerned in the propagation of influence, and that some media allow influence to take place across them better than others. The existence of a residual charge (Art. 61) can be explained either on the supposition that the dielectric is composed of heterogeneous particles which have unequal conducting powers, as Maxwell has suggested, or on the hypothesis that the molecules are actually subjected to a strain from which, especially if the stress be long-continued, they do not recover all at once. Kohlrausch and others have pointed out the analogy between this phenomenon and that of the "elastic recovery" of solid bodies after being subjected to a bending or a twisting strain. A fibre of glass, for example, twisted by a certain force, flies back when released to *almost* its original position, a slight sub-permanent set remains, from which, however, it slowly recovers itself, the rate of its recovery depending upon the amount and duration of the original twisting strain. A quartz fibre never shows any sub-permanent set. Hopkinson has shown that it is possible to superpose several residual charges, even charges of opposite signs, which apparently "soak out" as the strained material gradually recovers itself. Perry and Ayrton have also investigated the question, and have shown that the polarization charges in voltameters exhibit a similar recovery.* Air condensers exhibit no residual charges. Nor do plates of quartz cut from homogeneous crystal.

When a condenser is discharged a sound is often heard. This was noticed by Lord Kelvin in the case of air condensers; Varley and Dolbear have constructed telephones in which the rapid charge and discharge of

* It would appear, therefore, probable that Maxwell's suggestion of heterogeneity of structure, as leading to residual electrification at the bounding surface of the particles whose electric conductivities differ, is the true explanation of the "residual" charge. The phenomenon of elastic recovery may itself be due to heterogeneity of structure. Glass itself is a mixture of different silicates.

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molecular movement accompanies the changes of dielectric stress.

300. Electric Expansion. — Fontana noticed that the internal volume of a Leyden jar increased when it was charged. Priestly and Volta sought to explain this by suggesting that the attraction between the two charged surfaces compressed the glass and caused it to expand laterally. Duter showed that the amount of apparent expansion was inversely proportional to the thickness of the glass, and varied as the square of the potential difference. Quincke has recently shown that though glass and some other insulators exhibit electrical expansion, an apparent contraction is shown by resins and oily bodies under electrostatic stress. He connects with these properties the production of optical strain and of double refraction discovered by Kerr. (See Lesson on Electro-optics, Art. 525).

301. Submarine Cables as Condensers. — A submarine telegraph cable may act as a condenser, the ocean forming the outer coating, the internal wire the inner coating, while the insulating layers of guttapercha serve as dielectric. When one end of a submerged cable is connected to, say, the + pole of a powerful battery, electricity flows into it. Before any signal can be received at the other end, enough electricity must flow in to charge the cable to a considerable potential, an operation which may in the case of long cables require some seconds. Faraday predicted that this retardation would occur. It is, in actual fact, a serious obstacle to rapid signalling through Atlantic and other cables. Professor Fleeming Jenkin has given the following experimental demonstration of the matter. Let a mile of insulated cable wire be coiled up in a tub of water (Fig. 158), one end N being insulated. The other end is joined up through a long-coil galvanometer G to the + pole of a large battery, whose – pole is joined by a wire to the water in the tub. Directly this is done, the

needle of the galvanometer will show a violent deflexion, electricity rushing through it into the interior of the cable, and a – charge being accumulated on the outside of it where the water touches the guttapercha. For perhaps an hour the flow will go on, though diminishing, until the cable is fully charged. Now remove the battery, and instead join up *a* and *b* by a wire; the charge in the cable will rush out through the galvanometer, which will

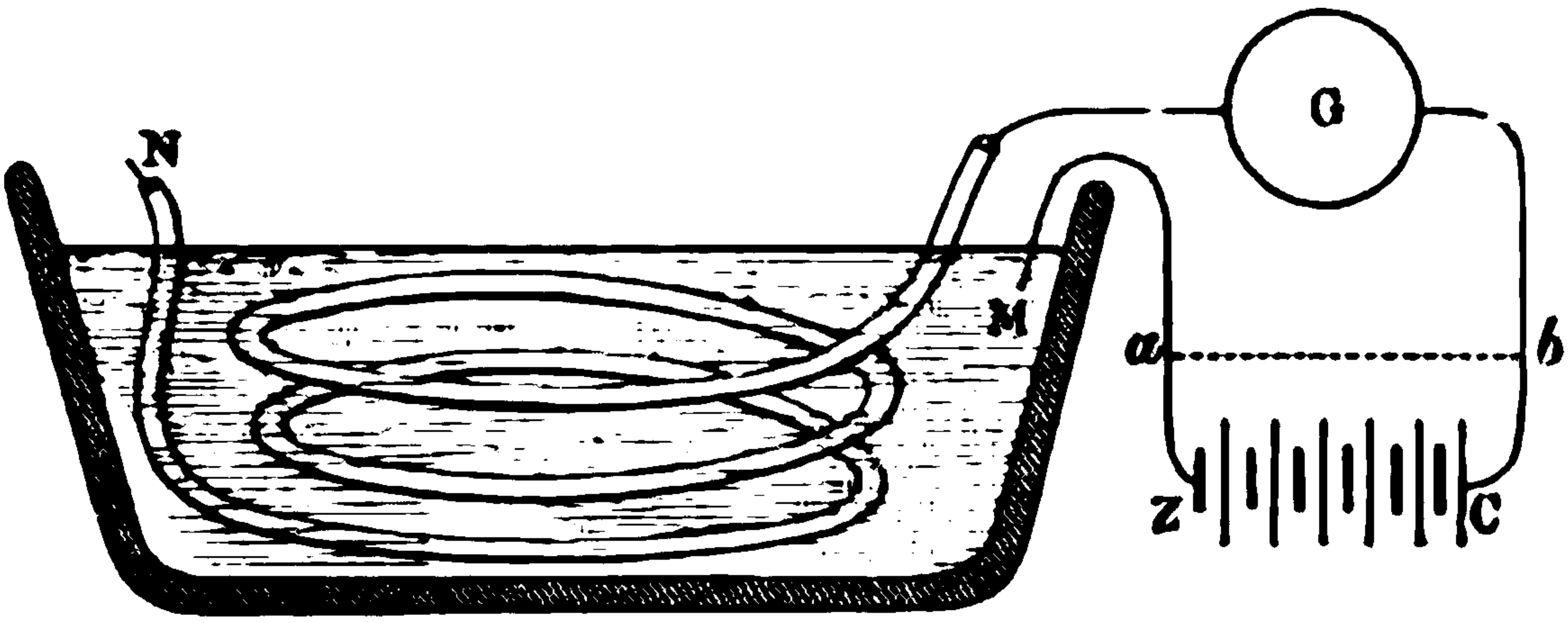


Fig. 158.

show an opposite deflexion, and the residual charge will continue "soaking out" for a long time.

Long land-lines carried overhead also possess a measurable capacity, and tend to retard the signals.

302. Use of Condensers.—To obviate this retardation and increase the speed of signalling in cables* several devices are adopted. Very delicate receiving instruments are used, requiring only a feeble current; for with the feebler batteries the actual charge given to the cable is less. In some cases a key is employed which, after every signal, immediately sends into the cable a charge of opposite sign, to sweep out, as it were, the charge left behind. Often a condenser of several microfarads' capacity is interposed in the circuit at each end of the cable to *curb* the signal, or make it shorter and sharper, and by its reaction assist the discharge. In duplex

* The capacity of the "Direct" Atlantic cable from Ballinskelligs (Ireland) to Nova Scotia is 992 microfarads.

signalling (Art. 503) the resistance and electrostatic capacity of the cable have to be met by balancing against them an "artificial cable" consisting of a wire of equal resistance, combined with a condenser of equal capacity. Messrs. Muirhead constructed for duplexing the Atlantic cable a condenser containing 100,000 square feet (over two acres of surface) of tinfoil. Condensers are also occasionally used on telegraph lines in single working to obviate disturbances from earth currents. They are constructed by placing sheets of tinfoil between sheets of mica or of paraffined paper, alternate sheets of foil being connected together. The paper is the finest bank-wove, carefully selected to be free from minute holes. Two thicknesses, drawn through a bath of the purest paraffin wax heated till it melts, are laid between each foil and the next; care being taken to exclude air bubbles. When a sufficient number have been assembled hot they are put under pressure to cool, and afterwards adjusted. Small condensers of similar construction are used in connexion with induction coils (Fig. 135).

303. Practical Unit of Capacity. — Electricians adopt a *unit of capacity*, termed one **farad**, based on the system of electromagnetic units. A condenser of one farad capacity would be raised to a potential of one volt by a charge of one coulomb of electricity.* In practice such a condenser would be too enormous to be constructed; the earth itself, as an isolated sphere, has a capacity of only $\frac{7}{10000}$ of a farad. As a *practical unit* of capacity is therefore chosen the **microfarad**, or one millionth of a farad; a capacity about equal to that of three miles of an Atlantic cable. Condensers of only $\frac{1}{3}$ microfarad capacity are about equal to one nautical mile of cable. They contain about 1200 square inches of foil. The



Fig. 159.

* See list of Practical Electromagnetic Units, Art. 354.

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The latter formula applies to any two parallel disks of surface S, whether circular or otherwise, provided they are *large* as compared with the distance *b* between them. To calculate down to microfarads the numbers given by any of the above must be divided by 900,000.

305. Energy of Discharge of Leyden Jar or Condenser. — It follows from the definition of potential, given in Art. 263, that in bringing up one + unit of electricity to the potential V, the work done is V *ergs*. This assumes, however, that the total potential V is not thereby raised, and on this assumption the work* done in bringing up Q units would be QV *ergs*. If, however, the potential is nothing to begin with, and is raised to V by the charge Q, the average potential during the operation is only $\frac{1}{2}$V; hence the total work done in bringing up the charge Q from zero potential to potential V is $\frac{1}{2}$QV *ergs*. Now, according to the principle of the conservation of energy, the work done in charging a jar or condenser with electricity is equal to the work which could be done by that quantity of electricity when the jar is discharged. Hence $\frac{1}{2}$QV represents also the energy of the discharge.

Since Q = VK, it follows that we may write $\frac{1}{2}$QV in the form $\frac{1}{2}\frac{Q^2}{K}$. That is to say, if a condenser of capacity K is charged by having a charge Q imparted to it, the energy of the charge is proportional directly to the square of the quantity, and inversely to the capacity of the condenser.

306. Symbol for Condenser. — Electricians use as symbols for condensers in diagrams of electric circuits those given in Fig. 160. The origin of these symbols is the alternate layers of tinfoils. The symbol on the right suggests six layers of foil, of which the first, third, and

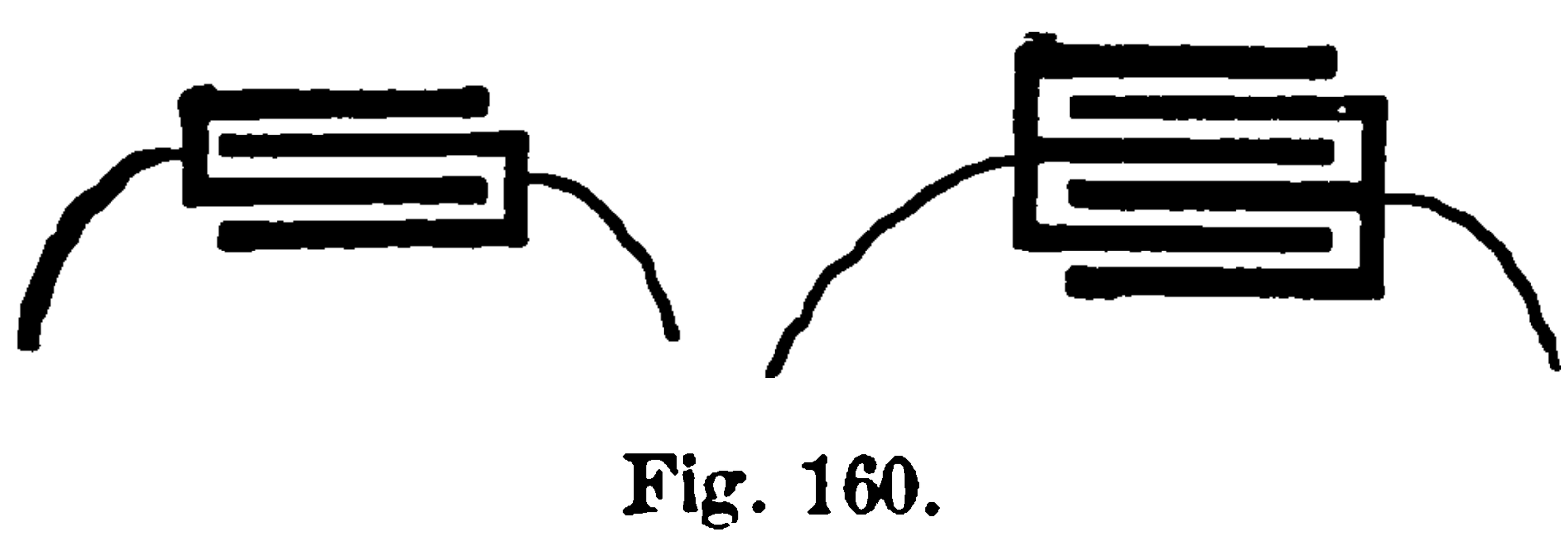


Fig. 160.

* If Q is given in *coulombs* and V in *volts*, the work will be expressed not in *ergs* but in *joules* (Art. 354).

fifth are joined together, and the second, fourth, and sixth are also joined together.

307. Capacities joined in Parallel.—To join two condensers together in parallel the positive foils of one are joined to the positive foils of the other, and their negative foils are also joined together. In Fig. 161 the two condensers K_1 and K_2 are joined in parallel. They will thus act simply like one large condenser of capacity $= K_1 + K_2$. Any charge flowing in on the + side will divide between the two in proportion to their capacities.

If two equal Leyden jars are charged to the same potential, and then their inside and outside coatings are respectively joined, their united charge will be the same as that of a jar of equal thickness, but having twice the amount of surface.

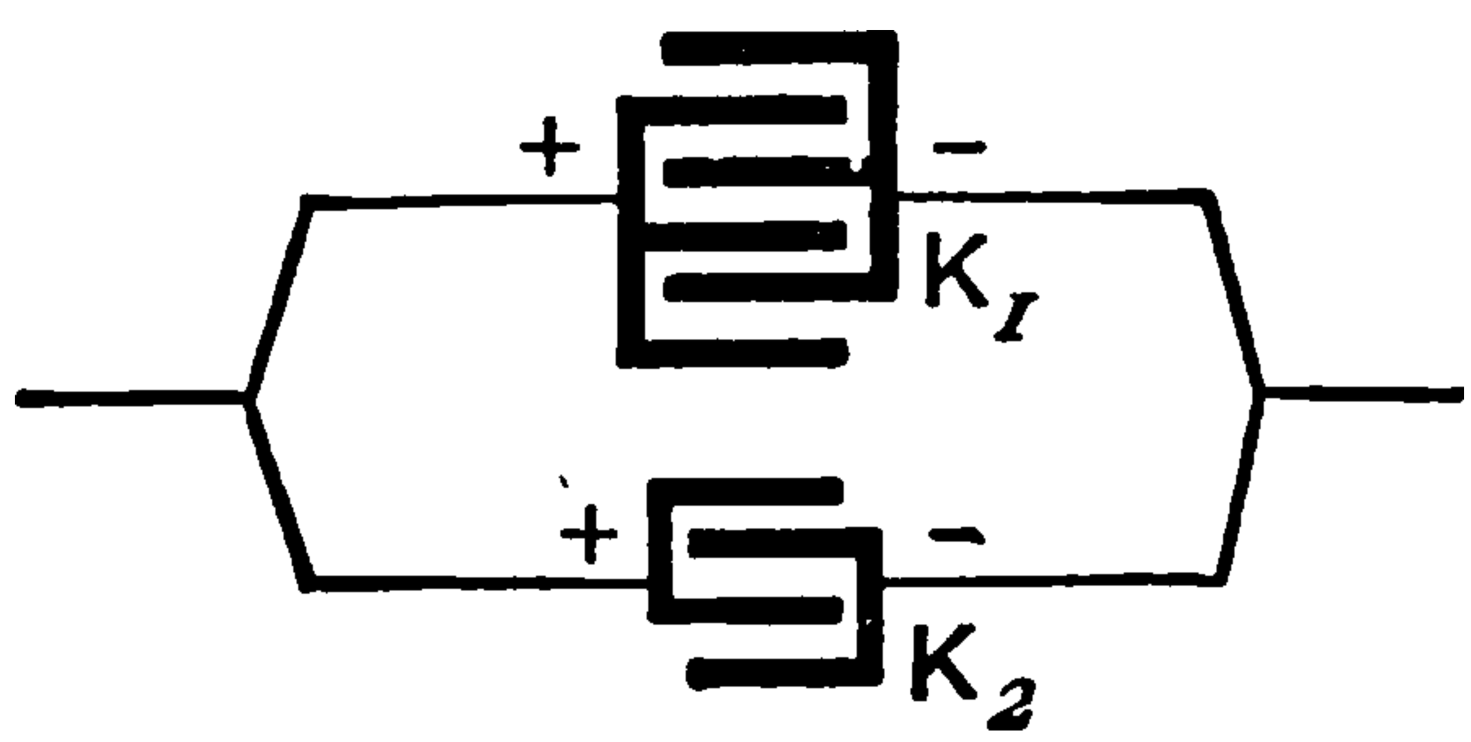


Fig. 161.

If a charged Leyden jar is placed similarly in communication with an uncharged jar of equal capacity, the charge will be shared equally between the two jars, and the passage of electricity from one to the other will be evidenced by the production of a spark when the respective coatings are put into communication. Here, however, half the energy of the charge is lost in the operation of sharing the charge, for each jar will have only $\frac{1}{2}Q$ for its charge and $\frac{1}{2}V$ for its potential; hence the energy of the charge of each, being half the product of charge and potential, will only be one quarter of the original energy. The spark which passes in the operation of dividing the charge is, indeed, evidence of the loss of energy; it is about half as powerful as the spark would have been if the first jar had been simply discharged, and it is just twice as powerful as the small sparks yielded finally by the discharge of each jar after the charge has been shared between them.

The energy of a charge of the jar manifests itself, as

stated above, by the production of a spark at discharge; the sound, light, and heat produced being the equivalent of the energy stored up. If discharge is effected slowly through a long thin wire of high resistance the air spark may be feeble, but the wire may be perceptibly heated. A wet string being a feeble conductor affords a slow and almost silent discharge; here probably the electrolytic conduction of the moisture is accompanied by an action resembling that of secondary batteries (Lesson 492) tending to prolong the duration of the discharge.

308. Capacities joined in Series. — If two condensers are joined in series they will act as a condenser having a lesser capacity than either of them separately. *Their joint capacity in series will be the reciprocal of the sum of the reciprocals of their capacities separately.*

Proof. — Let two condensers K_1 and K_2 be set in series (Fig. 162) between two points across which there is a difference of potential V. This difference of potential will be divided between the two inversely in proportion to their capacities, seeing that the quantities of electricity that are displaced into and out of their respective coatings are necessarily equal. Or, if Q be this quantity, and K_3 the effective or joint capacity of the two together, to find the latter, we have: —

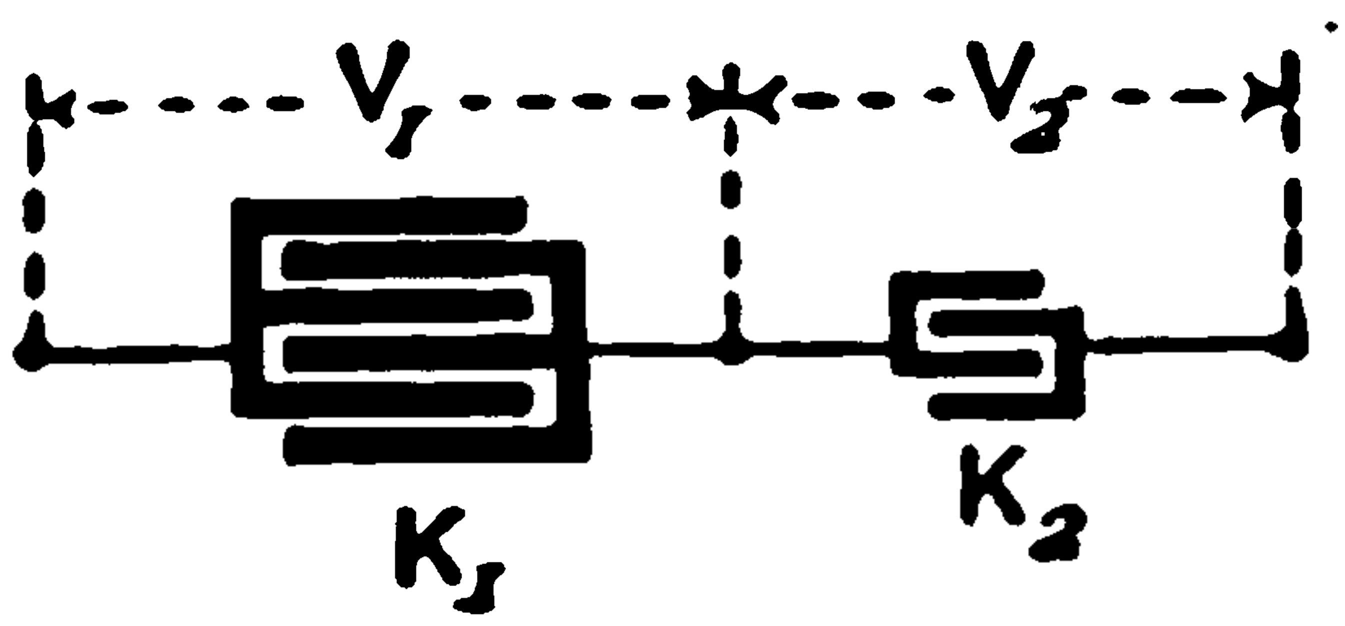


Fig. 162.

$$Q = V_1K_1 = V_2K_2 = VK_3 \quad . \quad . \quad . \quad (1)$$

and $$V = V_1 + V_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

From (1) we get

$$V_1 = VK_3/K_1,$$

and

$$V_2 = VK_3/K_2.$$

Inserting these in (2) we get

$$V = VK_3/K_1 + VK_3/K_2;$$

whence, dividing down by VK_3, we get

$$\frac{1}{K_3} = \frac{1}{K_1} + \frac{1}{K_2} \quad . \quad . \quad . \quad . \quad \text{Q.E.D.}$$

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pole, the operation is termed a "**conductive**" **discharge.** Under some circumstances a conductive discharge takes the nature of an oscillation to and fro (Art. 515).

311. Disruptive Discharge. — It has been shown how influence across a non-conducting medium is always accompanied by a mechanical stress upon the medium; the tension along the electric lines of force increasing as the square of the intensity of the electric field. If this stress is very great the non-conducting medium will suddenly give way and a *spark* will burst across it. Such a discharge is called a "**disruptive**" **discharge.**

A very simple experiment will set the matter in a clear light. Suppose a metal ball charged with + electrification to be hung by a silk string above a metal plate lying on the ground. If we lower down the suspended ball a spark will pass between it and the plate when they come very near together, and the ball will then be found to have lost all its previous charge. It was charged with a certain quantity of electricity; and as it had, when suspended out of the range of other conductors, a certain capacity (numerically equal to its radius in centimetres), the electricity on it would be at a certain potential (namely $= Q/K$), and the charge would be distributed uniformly all over it. The plate lying on the earth would be all the while at zero potential. But when the suspended ball was lowered down towards the plate the previous state of things was altered. In the presence of the + charge of the ball the potential* of the plate would rise, were it not that, by influence, just enough negative electrification appears on it to keep its potential still the same as that of the earth. The tension in the electric field will draw the + charge of the ball downwards, and alter the distribution of the charge, the surface-density becoming greater at the under surface of the ball

* The student must remember that, by the definition of potential in Art. 268, the potential at a point is the sum of all the separate quantities of electricity near it, divided each by its distance from the point.

and less on the upper. The capacity of the ball will be increased, and therefore its potential will fall correspondingly. The layer of air between the ball and the plate is acting like the glass of a Leyden jar. The more the ball is lowered down the greater is the accumulation of the opposite kinds of charge on each side of the layer of air, and the tension across the layer becomes greater and greater, until the limit of the dielectric strength is reached; the air suddenly gives way and the spark tears a path across.

312. **Convective Discharge.** — A third kind of discharge, differing from either of those above mentioned, may take place, and occurs chiefly when electricity of a high potential discharges itself at a pointed conductor by accumulating there with so great a density as to electrify the neighbouring particles of air; these particles then flying off by repulsion, conveying away part of the charge with them. Such *convective discharges* may occur either in gases or in liquids, but are best manifested in air and other gases at a low pressure, in tubes exhausted by an air pump.

The discharge of a quantity of electricity in any of the above ways is always accompanied by a transformation of its energy into energy of some other kind, — sound, light, heat, chemical actions, and other phenomena being produced. These effects must be treated in detail.

313. **Length of Spark.** — Generally speaking, the length of spark between two conductors increases with the difference between their potentials. It is also found to increase when the pressure of the air is diminished. Riess found the distance to increase in a proportion a little exceeding that of the difference of potentials. Lord Kelvin confirmed this by measuring by means of an "absolute electrometer" (Art. 287) the difference of potential necessary to produce a spark discharge between two parallel plates at different distances. De la Rue and Müller found with their great battery (Art. 186)

that with a difference of potential of 1000 volts the striking distance of the spark was only ·0127 centimetres (or about $\frac{1}{200}$ of an inch), and with a difference of 10,000 volts only 1·369. Their 11,000 silver cells gave a spark of 1·59 centim. (about $\frac{2}{3}$ of an inch) long. To produce a spark one mile long, through air at the ordinary pressure, would therefore require a difference of potential exceeding that furnished by 1,000,000,000 Daniell's cells!

The length of the spark differs in different gases, being nearly twice as long in hydrogen as in air at the same density. Or to produce in hydrogen a spark as long as one in air requires less voltage. On the other hand, carbonic acid gas, whilst it is stronger than air for short sparks, is weaker for long ones.

The potential needful to produce a spark of given length in a given gas is independent of the kind of metal used as electrodes, but depends upon their shape. If points are used instead of balls it is found that at equal voltage, points are best for long sparks, but are worst for short sparks.

According to Peace's observations a *minimum* potential of between 300 and 400 volts is necessary to start a spark, however short, in air. For sparks not under two millimetres in length the volts necessary to start a spark across a length of l centimetres may be approximately expressed by the equation—

$$V = 1500 + 30{,}000\, l.$$

The following table, calculated from the results of Heydweiller, gives the volts necessary to produce a spark in air at 15° C. and 76 centimetres pressure between two spheres of various sizes. The figures must be increased 1 per cent for a fall of 3 degrees of temperature, or for a rise of 8 millimetres of pressure.

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voltage is nearly high enough to produce a spark, reversing the poles will sometimes start a spark. Moreover, when once a spark has passed it is easier for a second one to follow on the same track. Probably the first spark produces chemical dissociations in its path which do not instantly pass away.

Hertz made the singular observation that ultra-violet light (*i.e.* actinic waves) falling upon the kathode surface assist it to discharge (see Art. 351).

A perfect vacuum is a perfect insulator — no spark will cross it. It is possible to exhaust a tube so perfectly that none of our electric machines or appliances can send a spark through the vacuous space even over so short a distance as one centimetre.

On the other hand, a great increase of pressure also increases the dielectric strength of air, and causes it to resist the passage of a spark. Cailletet compressed dry air at 40 to 50 atmospheres' pressure, and found that even the spark of a powerful induction coil failed to cross a space of ·05 centimetres' width.

314. Flames and Hot Air. — The *arc* produced by the passage of an electric current between two carbon poles is treated of in Art. 448. It is a species of flame which conducts the current from the tip of one carbon rod to the other, while volatilizing the carbon, and requires only some thirty to fifty volts for its maintenance. The alternate-current arc generated in air by high-frequency discharges at a potential of 10,000 to 50,000 volts is a different phenomenon, and is apparently an endothermic flame of nitrogen and oxygen burned together.

Sparks are longer and straighter through hot air than through cold. If air or other permanent gas is, however, heated in a closed vessel so that its density remains unaltered, the voltage needful to produce discharge remains the same; unless, indeed, the gas be heated to point of dissociation when discharge occurs at low voltage.

Flames and currents of very hot air, such as those rising from a red-hot piece of iron, are extremely good conductors of electricity, and act even better than metallic points in discharging a charged conductor. Gilbert showed that an electrified body placed near a flame lost its charge; and the very readiest way to rid the surface of a charged body of low conducting power of a charge imparted to it by friction or otherwise, is to pass it through the flame of a spirit-lamp. Faraday found negative electrification to be thus more easily discharged than positive. Flames powerfully negatively electrified are repelled from conductors, though not so when positively electrified. Sir W. Grove showed that a current is set up in a platinum wire, one end of which touches the tip, and the other the base, of a flame.

Guthrie showed that a red-hot iron ball cannot be positively, but may be negatively charged. When white-hot it will retain neither kind of charge.

315. Mechanical Effects.—Chief amongst the mechanical effects of the disruptive spark discharge is the shattering and piercing of glass and other insulators. The dielectric strength of glass, though much greater than that of air, is not infinitely great. A slab of glass 3 inches thick has been pierced by the discharge of a powerful induction coil. The so-called "toughened" glass has a greater dielectric strength than ordinary glass, and is more difficult to pierce. A sheet of glass may be readily pierced by a spark from a large Leyden jar or battery of jars, by taking the following precautions:—The glass to be pierced is laid upon a block of glass or resin, through which a wire is led by a suitable hole, one end of the wire being connected with the outer coating of the jar, the other being cut off flush with the surface. Upon the upper surface of the sheet of glass that is to be pierced another wire is fixed upright, its end being exactly opposite the lower wire, the other extremity of this wire being armed with a metal knob to receive the spark from

the knob of the jar or discharger. To ensure good insulation a few drops of paraffin oil, or of olive oil, are placed upon the glass round the points where the wires touch it. A piece of dry wood similarly treated is split by a powerful spark. A layer of oil resists being pierced as much as a layer of air five or six times as thick would do.

If a spark is led through a tightly-corked glass tube containing water, the tube will be shattered into small pointed fragments by the sudden expansion of the liquid.

Lullin observed two curious effects when a piece of cardboard is perforated by a spark between two metal points. *Firstly*, there is a slight burr raised on each side, as if the hole had been pierced from the middle outwards, as though the stress in the air had *pulled* at the card. *Secondly*, if the two points are not exactly opposite one another the hole is found to be nearer the *negative* point. But if the experiment is tried under the air pump in a vacuum, there is no such displacement of the hole; it is then midway exactly.

The mechanical action of the brush discharge at points is mentioned in Art. 47, and the mechanical effects of a current of electricity were described in Lesson XVI.

316. Chemical Effects.—The chemical actions produced by currents of electricity have been described in Lessons XIV. and XIX. Similar actions can be produced by the electric spark, and by the silent glow discharge (see Art. 319). Faraday showed, indeed, that electricity from all kinds of different sources produced the same kinds of chemical actions, and he relied upon this as one proof of the essential identity of the electricity produced in different ways. If sparks from an electric machine are received upon a piece of white blotting-paper moistened with a solution of iodide of potassium, brown patches are noticed where the spark has effected a chemical decomposition and liberated the iodine.

When a stream of sparks is passed through moist air

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sistance and accompanied by an evolution of heat. A few drops of ether in a metallic spoon are easily kindled by an electric spark. The spark from an electric machine, or even from a rubbed glass rod, suffices to kindle an ordinary gas-jet. In certain districts of America, during the driest season of the year, the mere rubbing of a person's shoes against the carpet, as he shuffles across the floor, generates sufficient electrification to enable sparks to be drawn from his body, and he may light the gas by a single spark from his outstretched finger. Gunpowder can be fired by the discharge of a Leyden jar, but the spark should be retarded by being passed through a wet thread, otherwise the powder will simply be scattered by the spark.

The *Electric Air-Thermometer*, invented by Kinnersley,* serves to investigate the heating powers of the discharge. It consists of a glass vessel enclosing air, and communicating with a tube partly filled with water or other liquid in order to observe changes of volume or of pressure. Into this vessel are led two metal rods, between which is suspended a thin wire, or a filament of gilt paper; or a spark can be allowed simply to cross between them. When the discharge passes the enclosed air is heated, expands, and causes a movement of the indicating column of liquid. The results of observation with these instruments are as follows: — The heating effect produced by a given charge in a wire of given length is inversely proportional to the square of the area of the cross section of the wire. The total heat evolved is jointly proportional to the charge, and to the potential through which it falls. In fact, if the entire energy of the discharge is expended in producing heat, and in doing no other kind of work, then the heat developed will be the thermal

* This instrument differs in no essential respect from that devised ninety years later by Riess, to whom the instrument is often accredited. Riess, however, deduced quantitative laws, while Kinnersley contented himself with qualitative observations.

equivalent of $\frac{1}{2}QV$ *ergs*, or $\frac{QV}{2J}$ *calories;* where J represents the mechanical equivalent of heat (J = 42 million; since 42×10^6 *ergs* = 1 *calorie*), and Q and V are expressed in C.G.S. units.

When a powerful discharge takes place through very thin wires, they may be heated to redness, and even fused by the heat evolved. Van Marum thus once heated 70 feet of wire by a powerful discharge. A narrow strip of tinfoil is readily fused by the charge of a large Leyden jar, or battery of jars. A piece of gold leaf is in like manner volatilized by a powerful discharge. Franklin utilized this property for a rude process of multiplying *portraits* or other patterns, which, being first cut out in card, were reproduced in a silhouette of metallic particles on a second card, by the device of laying above them a film of gold or silver leaf covered again with a piece of card or paper; a Leyden battery being then discharged through the leaf.

318. Luminous Effects. — The discharge exhibits many beautiful and varied luminous effects under different conditions. The *spark* of the disruptive discharge is usually a thin brilliant streak of light. When it takes place between two metallic balls, separated only by a short interval, it usually appears as a single thin and brilliant line. If, however, the distance be as much as a few centimetres, the spark takes an irregular zig-zag form. In any case its path is along the line of least resistance, the presence of minute motes of dust floating in the air being quite sufficient to determine the zig-zag character. Often the spark exhibits curious ramifications and forkings, of which an illustration is given in Fig. 163, which is drawn of one-eighth of the actual size of the spark obtained from an electrical machine. Photographs of lightning flashes almost always show similar branching. The branches always point toward the negative electrode. The discharge from a Leyden jar affords a much brighter,

shorter, noisier spark than the spark drawn direct from the collector of a machine. The length (see Art. 313) depends upon the potential, and upon the pressure and temperature of the air in which the discharge takes place. The brilliance depends chiefly upon the quantity of the discharge. The colour of the spark varies with the nature of the metal surfaces between which the discharge



Fig. 163.

takes place; for the spark tears away in its passage small portions of the metal surfaces, and volatilizes them. Between copper or silver terminals the spark takes a green tint, while between iron knobs it is of a reddish hue. Examination with the spectroscope reveals the presence in the spark of the rays characteristic of the incandescent vapours of the several metals.

319. Brush Discharge: Glow Discharge.—If an electric machine is vigorously worked, but no sparks be drawn from its collector, a fine diverging *brush* of pale blue light can be seen (in a dark room) streaming from the brass ball at the end of it farthest from the collecting comb; a hissing or crackling sound always accompanies this kind of discharge. The brush discharge consists of innumerable fine twig-like ramifications, presenting a form of which Fig. 164 gives a fine example. The brightness and size of the *brush* is increased by holding a flat plate of metal a little way from it. With

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conveys the electricity. This phenomenon, to which Faraday gave the name of the "*dark*" *discharge*, is very well seen when electricity is discharged through rarefied air and other gases in vacuum tubes.

A spark discharge may degenerate into a brush if the surface of the electrode becomes pitted or roughened by frequent discharges. Hence in all spark experiments it is important to keep the discharging balls *highly polished*.

320. Discharges in Partial Vacua. — If the discharge takes place in glass tubes or vessels from which the air has been partially exhausted, many remarkable and beautiful luminous phenomena are produced. A common form of vessel is the "electric egg" (Fig. 137), a sort of oval bottle that can be screwed to an air pump, and

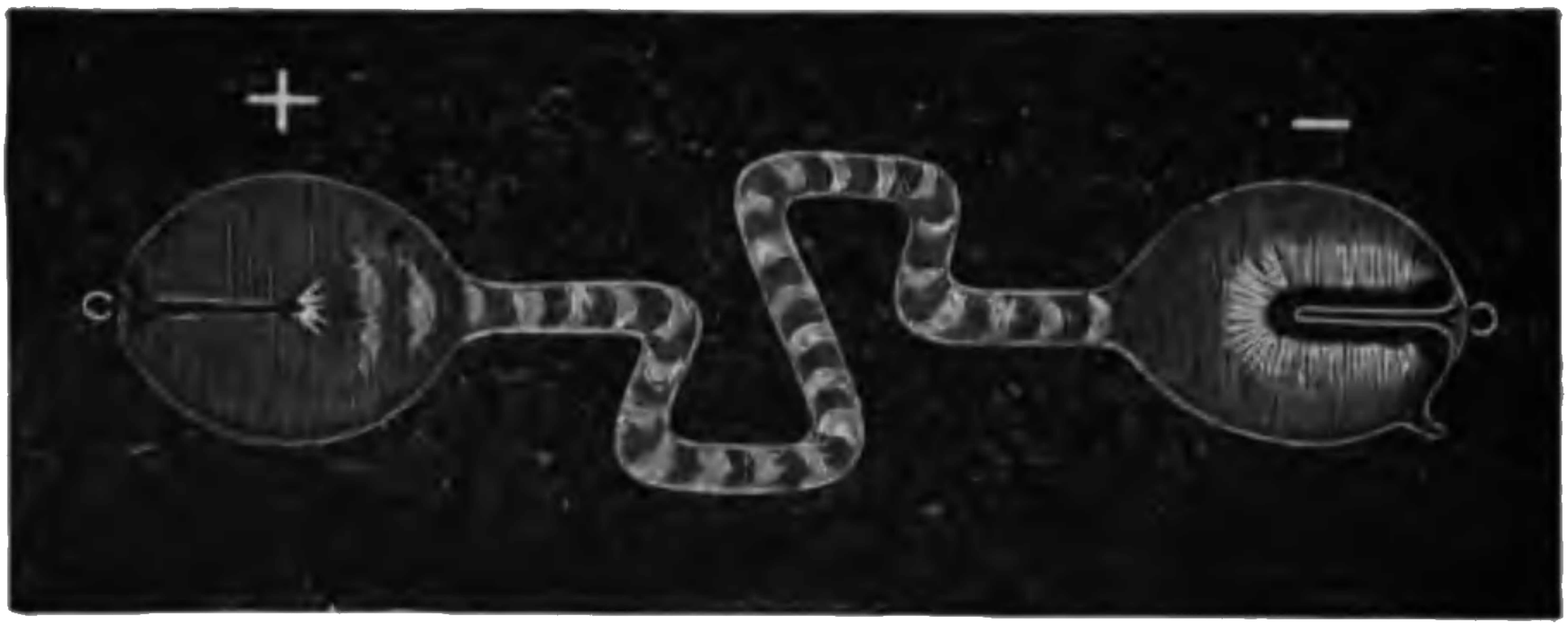


Fig. 165.

furnished with brass knobs to lead in the sparks. More often "vacuum tubes," such as those manufactured by the celebrated Geissler, are employed. These are merely tubes of thin glass blown into bulbous or spiral forms, provided with two electrodes of platinum wire fused into the glass, and sealed off after being partially exhausted of air by a mercurial air pump. Of these Geissler tubes the most useful consist of two bulbs joined by a narrow tube (Fig. 165), the luminous effects being usually more intense in the contracted portion. Such tubes are readily illuminated by discharges from an electrophorus or an

influence machine; but it is more common to work them with the spark of an induction coil (Fig. 135). A coil capable of throwing a $\frac{1}{2}$-inch spark in air will illuminate a vacuum tube 6 or 8 inches long. Where an alternate-current supply is available small transformers (Art. 228) wound to deliver $\frac{1}{50}$ ampere at 5000 volts serve admirably for lighting vacuum tubes.

Through such tubes, before exhaustion, the spark passes without any unusual phenomena being produced. As the air is exhausted the sparks become less sharply defined, and widen out to occupy the whole tube, becoming pale in tint and nebulous in form. The kathode exhibits a beautiful bluish or violet glow, separated from the conductor by a narrow *dark space*, while at the anode a single small bright star of light is all that remains. At a certain degree of exhaustion the light in the tube breaks up into a set of *striæ*, or patches of light of a cup-like form, which vibrate to and fro between darker spaces. In nitrogen gas the violet aureole glowing around the kathode is very bright, the rest of the light being rosy in tint. In oxygen the difference is not so marked. In hydrogen gas the tint of the discharge is bluish, except where the tube is narrow, where a beautiful crimson may be seen. With carbonic acid gas the light is remarkably white. Particles of metal are torn off from the kathode, and projected from its surface. The kathode is also usually the hotter when made of similar dimensions to the anode. If the anode is heated and the kathode kept cool no discharge will pass. The luminosity disappears from the rarefied air in the neighbourhood of a red-hot platinum spiral inside the tube. If the kathode gets white-hot the glow disappears, and the gas conducts freely without shining. It is also observed that the light of these discharges in vacuo is rich in those rays which produce phosphorescence and fluorescence. Many beautiful effects are therefore produced by blowing tubes in uranium glass, which fluoresces with a fine green light,

and by placing solutions of quinine or other fluorescent liquids in outer tubes of glass.

321. Phenomena in High Vacua. — Crookes has found that when exhaustion is carried to a very high degree the dark space separating the negative glow from the negative pole increases in width; and that across this space electrified molecules are projected in parallel paths normally from the surface of the kathode. If exhaustion be carried to such a high degree that the dark space fills the entire tube or bulb, the glass walls become beautifully phosphorescent. Diamonds, rubies, and even white powdered alumina placed in the tubes become brilliantly phosphorescent if the kathode discharge is directed upon them. And if bodies (whether opaque or transparent) be interposed in front of the electrode, sharply-defined *shadows* of these bodies are projected upon the opposite wall of the vessel, as if they stopped the way for some of the flying molecules, and prevented them from striking the opposite wall. In Fig. 166 the kathode K is a slightly convex disk of aluminium. In the path of the discharge is set a cross cut out of mica. Its shadow S appears on the end of the bulb, which phosphoresces all around the shadowed part. The anode may be either at A or *a*. Lightly-poised vanes are also driven round if placed in the path of the discharge. Crookes regarded this kathode discharge as exhibiting matter in an ultra-gaseous or *radiant* state. A disk placed in the line of the kathode discharge becomes thereby positively electrified. The kathode discharge is independent of the metal used as kathode, and is also independent of



Fig. 166.

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tinuous current from a battery of some thousands of cells (Art. 186) is used. There is a maximum of steadiness with a particular density of current. The striæ are hotter than the spaces between them. The number and position of the striæ vary, not only with the exhaustion, but with the difference of potentials of the electrodes. Each portion of the column of striæ acts as an independent discharge. When striæ are produced by the intermittent discharges of the induction coil, examination of them in a rotating mirror reveals that they move forward from the anode towards the kathode.

Schuster has shown that the discharge through gases is a process resembling that of electrolysis (Art. 237), being accompanied by breaking up of the gaseous molecules and incessant interchanges of atoms between them. The production of ozone (Art. 316) and the phenomena noticed at the kathode (Art. 321) give support to this view. Amongst other evidence is the striking discovery of Hittorf that quite a few cells can send a current through gas at ordinary pressures provided a spark-discharge is going on in the neighbourhood. J. J. Thomson finds that those gases which when heated are decomposed or molecularly dissociated, so that free atoms are present, are also good conductors. He regards chemical decomposition as an essential feature of gaseous discharge.

The discharges in vacuum tubes are affected by the *magnet* at all degrees of exhaustion, behaving like flexible conductors. Under certain conditions also, the discharge is *sensitive* to the presence of a conductor on the exterior of the tube, retreating from the side where it is touched. This sensitive state appears to be due to a periodic intermittence in the discharge; an intermittence or partial intermittence in the flow would also probably account for the production of striæ.

323. Velocity of Propagation of Discharge.—The earliest use of the rotating mirror to analyze phenomena of short duration was made by Wheatstone, who

attempted by this means to measure "the velocity of electricity" in conducting wires. What he succeeded in measuring was not, however, *the velocity of electricity*, but the time taken by a certain quantity of electricity to flow through a conductor of considerable resistance and capacity. Viewed in a rotating mirror, a spark of definite duration would appear to be drawn out into an elongated streak. Such an elongation was found to be visible when a Leyden jar was discharged through a copper wire half a mile long; and when the circuit was interrupted at three points, one in the middle and one at each end of this wire, three sparks were obtained, which, viewed in the mirror, showed a lateral displacement, indicating (with the particular rate of rotation employed) that the middle spark took place $\frac{1}{1152000}$ of a second later than those at the ends. Wheatstone argued from this a velocity of 288,000 miles per second. But Faraday showed that the apparent rate of propagation of a quantity of electricity must be affected by the capacity of the conductor; and he even predicted that since a submerged insulated cable acts like a Leyden jar (see Art. 301), and has to be charged before the potential at the distant end can rise, it will *retard* the apparent flow of electricity through it. Professor Fleeming Jenkin says of one of the Atlantic cables that, after contact with the battery is made at one end, no effect can be detected at the other for two-tenths of a second, and that then the received current gradually increases, until about three seconds afterwards it reaches its maximum, and then dies away. This retardation is proportional to the square of the length of the cable, being proportional both to its capacity and to its resistance; hence it becomes very serious on long cables, reducing the speed of signalling. There is in fact no definite assignable "velocity of electricity." In the case of wires suspended in air the velocity of propagation of any rapid electrical vibration is equal to the velocity of light. But in the case of slow vibrations, like those of telephonic

sounds being sent through land lines or cables, the velocity may be much less.

A very simple experiment will enable the student to realize the excessively short duration of the spark of a Leyden jar. Let a round disk of cardboard painted with black and white sectors be rotated very rapidly so as to look by ordinary light like a mere gray surface. When this is illuminated by the spark of a Leyden jar it appears to be standing absolutely still, however rapidly it may be turning. A flash of lightning is equally instantaneous; it is utterly impossible to determine at which end the flash begins.*

324. Electric Dust-Figures. — Electricity may creep slowly over the surface of bad conductors. Lichtenberg

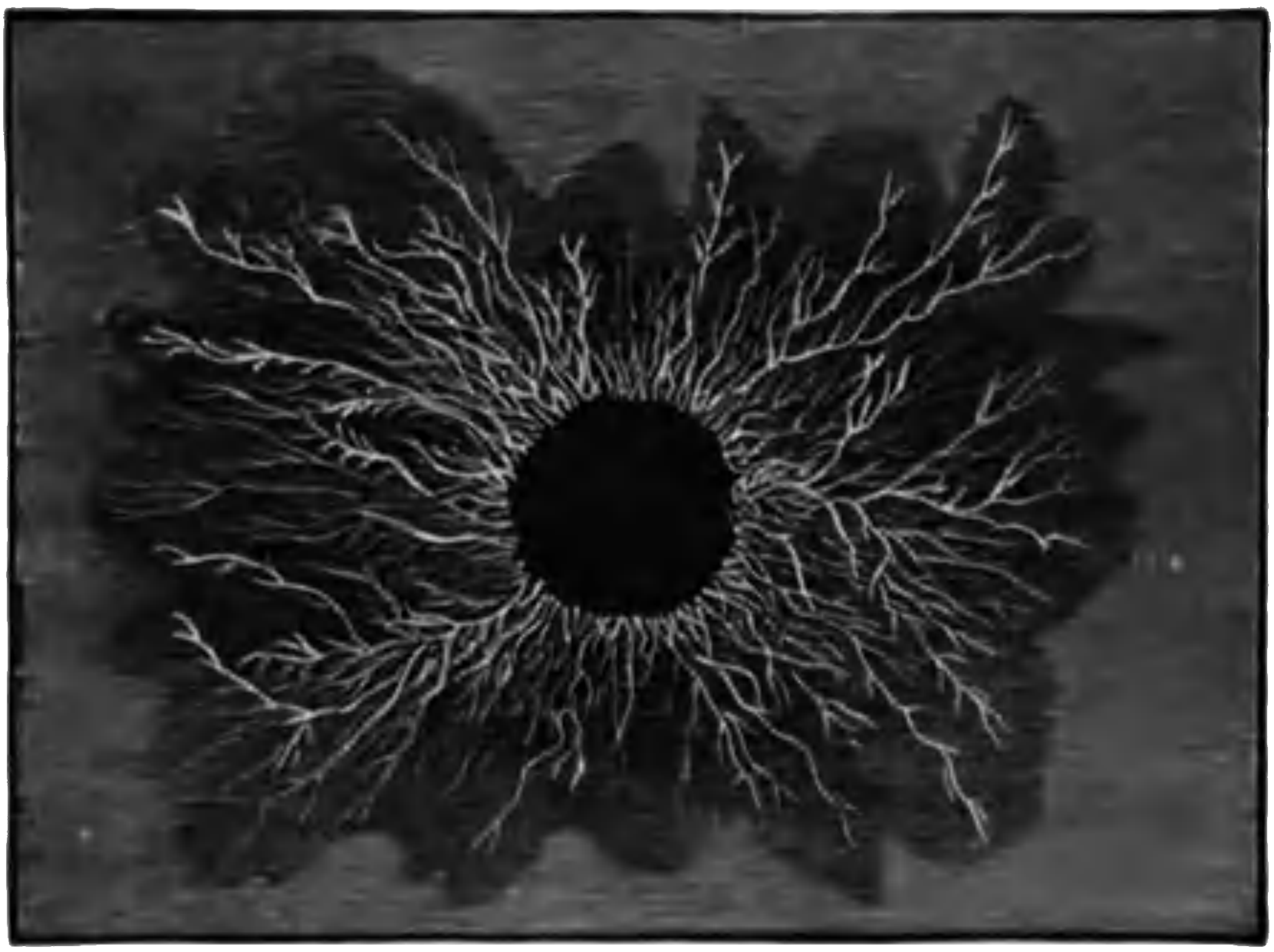


Fig. 167.

devised an ingenious and easy way of investigating the

* Sometimes the flash seems to strike downwards from the clouds, sometimes upwards from the earth. This is an optical illusion, resulting from the unequal sensitiveness to light of different portions of the retina of the eye.

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of the Leyden jar at the centre of a shellac plate that has previously been rubbed with flannel, the negative electrification being attracted upon all sides toward the central positive charge. These same powders may be used to investigate how surfaces have become electrified by rubbing, and how pyroelectric crystals (Art. 74) are electrified during cooling.

Powdered tourmaline, warmed and then sifted over a sheet of glass previously electrified irregularly, will show similar figures, though not so well defined.

Breath-figures can be made by electrifying a coin or other piece of metal laid upon a sheet of dry glass, and then breathing upon the glass where the coin lay, revealing a faint image of it on the surface of the glass.

F. J. Smith finds that if a coin or engraving laid face-down upon a photographic dry-plate is sparked with an induction coil, the plate receives an invisible image which can be photographically developed.

325. Physiological Effects.—The physiological effects of the current have been described in Lesson XX. Those produced by the spark-discharge are more sudden in character, but of the same general nature. Death is seldom the direct result. The shock causes a sudden cessation of respiration, resulting in suffocation as from drowning. The bodies of persons struck by the lightning spark frequently exhibit markings of a reddish tint where the discharge in passing through the tissues has lacerated or destroyed them. Sometimes these markings present a singular ramified appearance, as though the discharge had spread in streams over the surface at its entry.

326. Dissipation of Charge. — However well insulated a charged conductor may be, and however dry the surrounding air, it nevertheless slowly loses its charge, and in a few days will be found to be completely discharged. The rate of loss of charge is, however, not uniform. It is approximately proportional to the difference of potential between the body and the earth. Hence the rate of loss

is greater at first than afterwards, and is greater for highly-charged bodies than for those feebly charged. The law of dissipation of charge therefore resembles Newton's law of cooling, according to which the rate of cooling of a hot body is proportional to the difference of temperature between it and the surrounding objects. If the potential of the body be measured at equal intervals of time it will be found to have diminished in a decreasing geometric series; or the logarithms of the potentials at equal intervals of time will differ by equal amounts. The rate of loss is, however, greater at negatively-electrified surfaces than at positive.

This may be represented by the following equation:—

$$V_t = V_0 \epsilon^{-pt},$$

where V_0 represents the original potential and V_t the potential after an interval t. Here ϵ stands for the number 2·71828 . . . (the base of the natural logarithms), and p stands for the "coefficient of leakage," which depends upon the temperature, pressure, and humidity of the air. The same formula serves for the discharge of a condenser of capacity K through a resistance R; if p is written for 1/KR.

327. Positive and Negative Electrification. — The student will not have failed to notice throughout this lesson frequent differences between the behaviour of positive and negative electrification. The striking dissimilarity in the Lichtenberg's figures, the displacement of the perforation-point in Lullin's experiment, the unequal tendency to dissipation at surfaces, the unequal action of heat on positive and negative charges, the remarkable differences in the various forms of brush and glow discharge, are all points that claim attention. Gassiot described the appearance in vacuum tubes as of a force emanating from the negative pole. Crookes's experiments in high vacua show molecules to be violently discharged from the negative electrode, the vanes of a little fly enclosed in such tubes being moved from the side struck by the negative discharge. Holtz found that

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of separate particles, can receive a bodily charge. The air in a room in which an electric machine is worked is found afterwards to be charged. The clouds are usually charged more or less with electricity, derived, probably, from evaporation going on at the earth's surface. The minute particles of water floating in the air become more highly charged. As they fall by gravitation and unite together, the strength of their charges increases. Suppose eight small drops to join into one. That one will have eight times the quantity of electricity distributed over the surface of a single sphere of twice the radius (and, therefore, of twice the capacity, by Art. 272) of the original drops; and its electrical potential will therefore be four times as great. Now a mass of cloud may consist of such charged spheroids, and its potential may gradually rise, therefore, by the coalescence of the drops, and the electrification at the lower surface of the cloud will become greater and greater, the surface of the earth beneath acting as a condensing plate and becoming charged, by influence, with the opposite kind of electrification. Presently the difference of potential becomes so great that the intervening strata of air give way under the strain, and a disruptive discharge takes place at the point where the air offers least resistance. This lightning spark, which may be more than a mile in length, discharges only the electricity that has been accumulating at the surface of the cloud, and the other parts of the cloud will now react upon the discharged portion, producing internal attractions and internal discharges. The internal actions thus set up will account for the usual appearance of a thundercloud, that it is a well-defined flat-bottomed mass of cloud which appears at the top to be boiling or heaving up with continual movements.

331. Lightning and Thunder. — Three kinds of lightning have been distinguished by Arago: (i.) The *Zig-zag flash* or "*Forked lightning*," of ordinary occurrence. The zig-zag form is probably due either to the

presence of solid particles in the air or to local electrification at certain points, making the crooked path the one of least resistance. (ii.) *Sheet lightning*, in which whole surfaces are lit up at once, is probably only the reflexion on the clouds of a flash taking place at some other part of the sky. It is often seen on the horizon at night, reflected from a storm too far away to produce audible thunder, and is then known as "summer lightning." (iii.) *Globular lightning*, in the form of *balls of fire*, which move slowly along and then burst with a sudden explosion. This form is very rare, but must be admitted as a real phenomenon, though some of the accounts of it are greatly exaggerated. Similar phenomena on a small scale have been produced (though usually accidentally) with electrical apparatus.

The sound of the thunder may vary with the conditions of the lightning spark. The spark heats the air in its path, causing sudden expansion and compression all round, followed by as sudden a rush of air into the partial vacuum thus produced. If the spark be straight and short, the observer will hear but one short sharp *clap*. If its path be a long one and not straight, he will hear the successive sounds one after the other, with a characteristic *rattle*, and the echoes from other clouds will come *rolling* in long afterwards. The lightning-flash itself never lasts more than $\frac{1}{100000}$ of a second, but sometimes is oscillatory in character (see Art. 515).

The damage done by a lightning-flash when it strikes an imperfect conductor appears sometimes as a disruptive mechanical disintegration, as when the masonry of a chimney-stack or church-spire is overthrown, and sometimes as an effect of heat, as when bell-wires and objects of metal in the path of the lightning-current are fused. The physiological effects of sudden discharges are discussed in Arts. 255 and 325.

The "return-stroke" experienced by persons in the neighbourhood of a flash is explained in Art. 29.

332. Lightning Conductors. — The first suggestion to protect property from destruction by lightning was made by Franklin in 1749, in the following words: —

"May not the knowledge of this power of points be of use to mankind, in preserving houses, churches, ships, etc., from the stroke of lightning, by directing us to fix on the highest parts of those edifices upright rods of iron made sharp as a needle, and gilt to prevent rusting, and from the foot of those rods a wire down the outside of the building into the ground, or round one of the shrouds of a ship, and down her side till it reaches the water? Would not these pointed rods probably draw the electrical fire silently out of a cloud before it came nigh enough to strike, and thereby secure us from that most sudden and terrible mischief?"

Maxwell proposed to cover houses with a network of conducting wires, without any main conductor, the idea being that then the interior of the building will, like Faraday's hollow cube (Art. 34), be completely protected from electric force. Much controversy has arisen of late respecting lightning-rods. Professor Oliver Lodge maintains the lightning flash to be of the nature of an electric oscillation (Art. 515) rather than a current. If so, the conductor of least resistance is not necessarily the best lightning-rod. Professor Lodge and the author independently, and for different reasons, recommend iron in preference to copper for lightning-rods.

The following points summarize the modern views on the subject: —

1. All parts of a lightning conductor should be of one and the same metal, avoiding joints as far as possible, and with as few sharp bends or corners as may be.

2. The use of copper for lightning-rods is a needless extravagance. Iron is far better. Ribbon is slightly better than round rod; but ordinary galvanized iron telegraph-wire is good enough.

3. The conductor should terminate not merely at the highest point of a building, but be carried to all high points. It is unwise to erect very tall pointed rods projecting several feet above the roof.

4. A good deep *wet* "earth" should be provided, independent of gas or water pipes, to which the conductor should be led down.

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of the glass of a charged jar, we should find that the values of the potential changed in regular order from a + value at one side to a – value at the other, there being a point of zero potential about half way between the two. Now, the air in fine weather always gives + indications, and the potential of it is higher the higher we go to measure it. Cavallo found higher electrification just outside the cupola of St. Paul's Cathedral than at a lower point of the building. Lord Kelvin found the potential in the island of Arran to increase from 23 to 46 volts for a rise of one foot in level; but the difference of potential was sometimes eight or ten times as much for the same difference of level, and changed rapidly, as the east wind blew masses of cloud charged with + or – electricity across the sky. Joule and Kelvin, at Aberdeen, found the rise of potential to be equal to 40 volts per foot, or 1·3 volts per centimetre rise of level.

During fine weather a negative electrification of the air is extremely rare. Beccaria only observed it six times in fifteen years, and then with accompanying winds. But in broken weather and during rain it is more often – than +, and exhibits great fluctuations, changing from – to +, and back, several times in half an hour. A definite change in the electrical conditions usually accompanies a change of weather. "If, when the rain has ceased (said Ceca), a strong excessive (+) electricity obtains, it is a sign that the weather will continue fair for several days."

334. Methods of Observation.—The older observers were content to affix to an electroscope (with gold leaves or pith-balls) an insulated pointed rod stretching out into the air above the ground, or to fly a kite, or (as Becquerel did) to shoot into the air an arrow communicating with an electroscope by a fine wire, which was removed before it fell. Gay Lussac and Biot lowered a wire from a balloon, and found a difference of potential between the upper and lower strata of the air. None

of these methods is quite satisfactory, for they do not indicate the potential at any *one* point. To bring the tip of a rod to the same potential as the surrounding air, it is necessary that material particles should be discharged from that point for a short time, each particle as it breaks away carrying with it a + or a – charge until the potentials are equalized between the rod and the air at that point. Volta did this by means of a small flame at the end of an exploring rod. Lord Kelvin has employed a "water-dropper," an insulated cistern provided with a nozzle protruding into the air, from which drops issue to equalize the potentials: in winter he uses a small roll of smouldering touch-paper. Dellmann adopted another method, exposing a sphere to influence by the air, and then insulating it, and bringing it within-doors to examine its charge. Peltier adopted the kindred expedient of placing, on or near the ground, a delicate repulsion-electrometer, which during exposure was connected to the ground, then insulated, then removed indoors for examination. This process really amounted to charging the electrometer *by influence* with electrification of opposite sign to that of the air. The "quadrant" electrometer, described in Art. 288, and a "portable" electrometer on the attracted-disk principle, are now used for observations on atmospheric electricity. Using a water-dropping collector and a Kelvin electrometer, Everett made a series of observations in Nova Scotia, and found the highest + electrification in frosty weather, with a dry wind charged with particles of ice.

335. **Diurnal Variations.**—Quetelet found that at Brussels the daily indications (during fine weather) showed two *maxima* occurring in summer at 8 A.M. and 9 P.M., and in winter at 10 A.M. and 6 P.M. respectively, and two *minima* which in summer were at the hours of 3 P.M. and about midnight. He also found that in January the electricity was about thirteen times as strong as in June. At Kew there is a maximum at 8 A.M. in

summer, and at 10 A.M. in winter; and a second minimum at 10 P.M. in summer and 7 P.M. in winter. The *maxima* correspond fairly with hours of changing temperature, the *minima* with those of constant temperature. In Paris, M. Mascart finds but one maximum, just before midnight: at sunrise the electricity diminishes until about 3 P.M., when it has reached a minimum, whence it rises till nightfall.

Our knowledge of this important subject is still very imperfect. We do not even know whether all the changes of the earth's electrification relatively to the air are due to causes operating above or below the earth's surface. Simultaneous observations at different places and at different levels are greatly wanted.

336. The Aurora.—In all the northern regions of the earth the *Aurora borealis*, or "Northern Lights," is an occasional phenomenon; and within and near the Arctic circle is of almost nightly occurrence. Similar lights are seen in the south polar regions of the earth, and are denominated *Aurora australis*. As seen in European latitudes, the usual form assumed by the aurora is that of a number of ill-defined streaks or streamers of a pale tint (sometimes tinged with red and other colours), either radiating in a fan-like form from the horizon in the direction of the (magnetic) north, or forming a sort of arch across that region of the sky, of the general form shown in Fig. 169. A certain flickering or streaming motion is often discernible in the streaks. Under very favourable circumstances the aurora extends over the entire sky. The appearance of an aurora is usually accompanied by a *magnetic storm* (Art. 159), affecting the compass-needles over whole regions of the globe. This fact, and the position of the auroral arches and streamers with respect to the magnetic meridian, directly suggest an electric origin for the light,—a conjecture which is confirmed by the many analogies found between auroral phenomena and

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The spectroscope shows the auroral light to be due to gaseous matter, its spectrum consisting of a few bright lines not referable with certainty to any known terrestrial substance, but having a general resemblance to those seen in the spectrum of the electric discharge through rarefied dry air.

The most probable theory of the aurora is that originally due to Franklin; namely, that it is due to electric discharges in the upper air, in consequence of the differing electrical conditions between the cold air of the polar regions and the warmer streams of air and vapour raised from the level of the ocean in tropical regions by the heat of the sun.

According to Nordenskiold the terrestrial globe is perpetually surrounded at the poles with a ring or crown of light, single or double, to which he gives the name of the "aurora-glory." The outer edge of this ring he estimates to be at 120 miles above the earth's surface, and its diameter about 1250 miles. The centre of the aurora-glory is not quite at the magnetic pole, being in lat. 81° N., long. 80° E. This aurora-glory usually appears as a pale arc of light across the sky, and is destitute of the radiating streaks shown in Fig. 169, except during magnetic and auroral storms.

An artificial aurora has been produced by Lemström, who erected on a mountain in Lapland a network of wires presenting many points to the sky. By insulating this apparatus and connecting it by a telegraph-wire with a galvanometer at the bottom of the mountain, he was able to observe actual currents of electricity when the auroral beam rose above the mountain.

CHAPTER V

ELECTROMAGNETICS

Lesson XXVI. — *Magnetic Potential*

337. Electromagnetics. — That branch of the science of electricity which treats of the relation between electric currents and magnetism is termed **Electromagnetics.** In Arts. 128 to 140 the laws of magnetic forces were explained, and the definition of "unit pole" was given. It is, however, much more convenient, for the purpose of study, to express the interaction of magnetic and electromagnetic systems in terms not of "force" but of "*potential*"; *i.e.* in terms of their power to do work. In Art. 263 the student was shown how the electric potential due to a quantity of electricity may be evaluated in terms of the work done in bringing up as a test charge a unit of + electricity from an infinite distance. **Magnetic potential** can be measured similarly by the ideal process of bringing up a unit magnetic pole (N-seeking) from an infinite distance, and ascertaining the amount of work done in the operation. Hence a large number of the points proved in Lesson XXI. concerning electric potential will also hold true for magnetic potential. The student may compare the following propositions with the corresponding ones in Articles 263 to 268: —

(a) *The magnetic potential at any point is the work that must be spent upon a unit magnetic* (N-seeking)

pole in bringing it up to that point from an infinite distance.

(b) *The magnetic potential at any point due to a system of magnetic poles is the sum of the separate magnetic potentials due to the separate poles.*

The student must here remember that the potentials due to S-seeking poles will be of opposite sign to those due to N-seeking poles, and must be reckoned as negative.

(c) *The (magnetic) potential at any point due to a system of magnetic poles may be calculated* (compare with Art. 263) *by summing up the strengths of the separate poles divided each by its own distance from that point.* Thus, if poles of strengths m', m'', m''', etc., be respectively at distances of r', r'', r''', . . . from a point P, then the following equation gives the potential at P:—

$$V_P = \frac{m'}{r'} + \frac{m''}{r''} + \frac{m'''}{r'''} + \cdots\cdots\cdots$$

or $V_P = \Sigma \frac{m}{r}$.

(d) *The difference of (magnetic) potential between two points is the work to be done* on *or* by *a unit (N-seeking) pole in moving it from one point to the other.* It follows that if m units of magnetism are moved through a difference of potential V, the work W done will be

$$W = mV.$$

(e) *Magnetic force on unit pole is the rate of change of (magnetic) potential per unit of length:* it is numerically equal to the intensity of the field. Since by Art. 141,

$$f = m\mathrm{H},$$

and work is the product of a force into the length

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a number of conical regions, each having their apex at that pole; and through each cone, as through a tube, a certain number of lines of force will pass. Such a conical space may be called a "tube" of force. The total number of magnetic lines within any tube of force is called the *magnetic flux.** No matter where you cut across a tube of force, the cross-section will cut through the enclosed flux, though the lines diverge more widely as the tube widens. Hence,

(g) *The magnetic flux across any section of a tube of force is constant wherever the section be taken.*

In case the magnetism is not concentrated at one point, but distributed over a surface from which the tubes start, we shall have to speak of the "amount of magnetism" rather than of the "strength of pole," and in such a case the

(h) *Magnetic density is the amount of magnetism per unit of surface.* In the case of a simple magnetic shell over the face of which the magnetism is distributed with uniform density, the "strength" of the shell will be equal to the thickness of the shell multiplied by the surface-density.

338. Intensity of Field. — We have seen (Art. 115) that every magnet is surrounded by a certain "field," within which magnetic force is observable. We may completely specify the properties of the field at any point by measuring the *strength* and the *direction* of that force, — that is, by measuring the "intensity *of the field*" and the direction of the lines of force. *The "intensity of the field" at any point is measured by the force with which it acts on a unit pole placed at that point.* Hence, *unit intensity of field is that intensity of field which acts on a unit pole with a force of one dyne.* There is therefore a field of

* The *magnetic flux* is by some writers called the *total induction;* but the word induction ought to be kept for the *operation* of inducing.

unit intensity at a point one centimetre distant from the pole of a magnet of unit strength. Suppose a magnet pole, whose strength is m, placed in a field at a point where the intensity is **H**, then the force will be m times as great as if the pole were of unit strength, and

$$f = m \times \mathbf{H}.$$

To aid the imagination by a graphic conception we adopt Faraday's notion of representing the properties of a magnetic field by supposing lines to be drawn so that they represent the *direction* and *intensity* of the field by the *direction* and *density* of the lines. This leads to the empirical rule to draw as many magnetic lines to the square centimetre (of cross section) as there would be dynes of force on unit pole. A field of **H** units means one where there would be **H** dynes on unit pole, or **H** lines per square centimetre. *It follows that a unit magnetic pole will have* 4π *lines of force proceeding from it:* for there is unit field at unit distance away, or one magnetic line per square centimetre; and there are 4π square centimetres of surface on a sphere of unit radius drawn round the pole. A magnet, whose pole-strength is m, has $4\pi m$, or $12{\cdot}57 \times m$, lines running through the steel, and diverging at its pole. The above-mentioned rule is the origin of the 4π symbol which comes in so often into electromagnetic formulæ. Suppose a narrow crevasse between the faces of two opposing magnets, each having σ units of magnetism per square centimetre of their pole surfaces. The field in the space between will have the value

$$\mathbf{H} = 4\pi\sigma.$$

339. Work done by Conductor carrying Current when it cuts across the Lines of a Magnetic Field.— By definition (Art. 263) it follows that the work W done in moving Q units of electricity against an electromotive-force V is equal to QV. Suppose that this electro-

motive-force is due to the conductor cutting **N** magnetic lines during time t. Then if the motion be uniform and the average current during the time is called C, it follows that $Q = Ct$. And the average electromotive-force is (see Art. 225) $= \mathbf{N}/t$. Inserting these values we get

$$W = Ct \times \mathbf{N}/t,$$

or

$$W = C\mathbf{N};$$

or, in words, *the work done in moving a current across a magnetic flux is equal to the product of the current into the total number of magnetic lines cut.* It will be noted that the work is the same whether the time is long or short. If C and **N** are in absolute (C.G.S.) units, W will be in *ergs*.

340. Force exerted by Magnetic Field on Wire carrying Current.—If a wire is moved sideways across the lines of a magnetic field, through a distance x it will sweep out an area equal to its own length l multiplied by x. And if **H** is the number of magnetic lines per square centimetre the total number of lines cut will be $= \mathbf{H}lx$; and the work done if the wire carries current C will be $= C\mathbf{H}lx$. But if work W is done in moving the wire through distance x the force f exerted will be W/x. Hence the force on the wire will be

$$f = C\mathbf{H}l;$$

or, in words, *the force is proportional to the current, to the intensity of the field, and to the length of wire in the field.* It is a force that tends to drag the wire laterally, acting at right angles to the wire and to the lines of the field.

This action is of course due to stresses going on in the medium, and is worthy of further thought. Consider the magnetic field in a gap between a large N-pole and a similar S-pole. The lines will go nearly uniformly straight across. Let a current flow in a copper wire that lies across the field. In Fig. 170 the wire is seen end-

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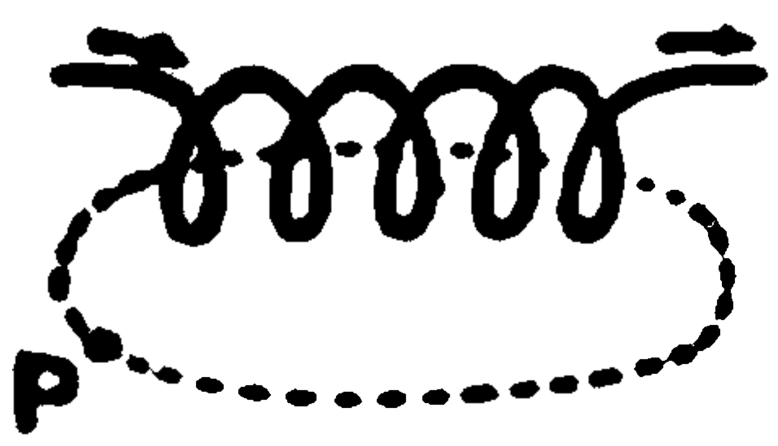
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turns of the magnetizing coil. The work done on a unit pole in moving it once around the closed path, against the magnetic forces of the system, is a measure of *the power of that system to magnetize;* or, in other words, is a measure of its **magnetomotive-force.** Such a closed path may lie, according to circumstances, either wholly in air, or partly in air partly in iron, or wholly in iron. The argument is entirely independent of any materials lying along the ideal path.


Fig. 171.

Now imagine this unit-pole, with its 4π magnetic lines radiating out of it, to be passed along the closed path (Fig. 171) from P, through the spirals to P again. Each turn of the coil will cut each of the magnetic lines once, and therefore, by Arts. 338 and 339, the total work done will be

$$W = 4\pi CS/10,$$

where we divide by 10 to bring *amperes* to C.G.S. units. Or, since $4\pi = 12{\cdot}57$, we get the rule—*the magnetomotive-force* of a coil is equal to* 1·257 *times the ampere-turns.*

342. Intensity of Field in a Long Tubular Coil, or Solenoid.—A spiral coil wound on a tube is called a *solenoid.* It has, when a current circulates in its coils, a magnetic field along the inside of it, and is, in fact, so long as the current circulates, a magnet without iron. This magnetic field, if the spiral is a very long one—say 20 times as long as the diameter of the spirals,—is very uniform all along the interior, except just toward the ends, where it becomes weaker. To find the intensity of the field **H**, we may remember that (Art. 337 e) the work done on a unit-pole in moving it through a length l of field **H** is equal to **H**l. But the work done in

* Since this magnetomotive-force is made up of a number of small elements distributed variously along the path it is sometimes called the *line-integral of the magnetizing forces.*

moving it along the tubular coil of length l is practically equal to that done around the closed path, since nearly all the forces are met along the part of the path inside. Hence we may equate $4\pi CS/10$ to $\mathbf{H}l$; giving the result

$$\mathbf{H} = \frac{4\pi}{10} \times \frac{CS}{l},$$

or *the intensity of the field in a long spiral is equal to* 1·257 *times the number of ampere-turns per centimetre of length.*

At the mouth of a long spiral the intensity of the field is exactly half what it is midway between the ends.

343. Magnetic Field due to Indefinitely Long Straight Current. Law of Inverse Simple Distance. — Consider a unit-pole at point P at a distance r (Fig. 172) from an indefinitely long straight conductor carrying a current of C amperes. The force tending to make the pole circulate around the wire may be calculated very simply as follows. If the unit-pole were to be moved once around the wire on a circular path with radius r, each one of the 4π magnetic lines that radiate from it would be cut once by the wire. Hence, by Art. 339, the work done in one such revolution would be equal to $4\pi C/10$. But this work has been done by moving the unit, against the forces of the system, along a path the length of which is $2\pi r$; wherefore

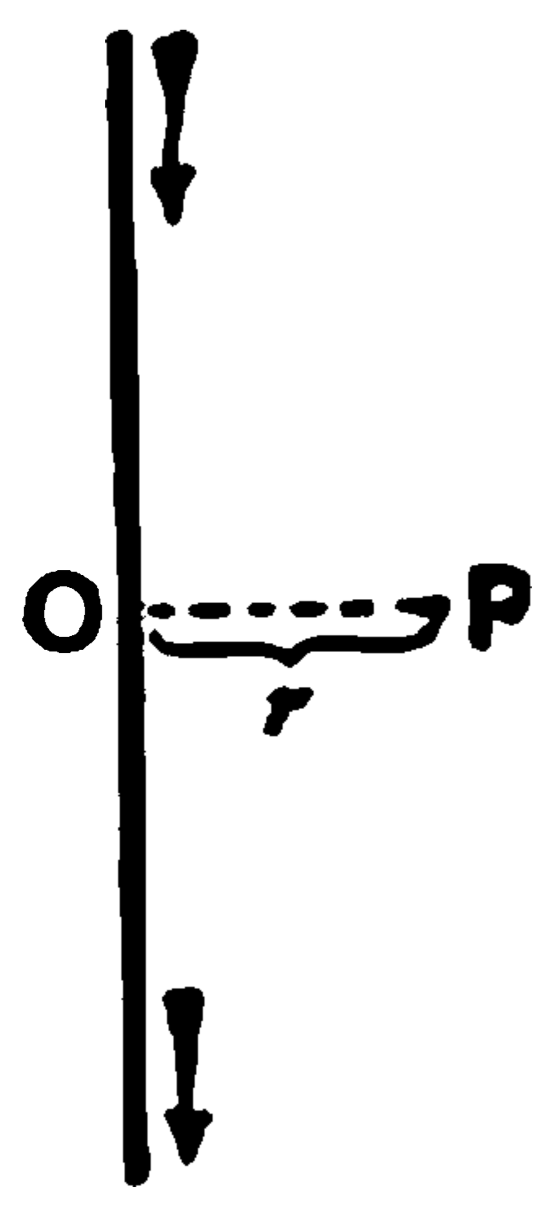


Fig. 172.

$$W = f \times 2\pi r = 4\pi C/10,$$

whence

$$f = 2C/10r.$$

From this it appears that the force on unit-pole, and therefore the intensity of the field, is *directly proportional to the current*, and *varies inversely as the simple distance* from the wire.

Example. — The force exerted on a pole of 1200 units of

magnetism at a distance of 4 centimetres from a long straight wire carrying current of 60 amperes will be 3600 dynes, or 3·52 grammes.

The fact that the force varies inversely as the simple distance, and not as the square, was experimentally discovered by Biot and Savart in 1820.

Around such a straight conductor the magnetic field consists of a cylindrical whirl of circular lines (Art. 202), their density decreasing as their radius increases. Outside a straight wire carrying a 10 ampere current the values of **H** are: 2 at 1 cm.; 1 at 2 cm.; 0·4 at 5 cm., and so forth. The pole tends to move circularly around the wire.

344. Mutual Action of Magnet-pole and of Element of Current.—Consider an element of current, that is to say, an indefinitely short piece of a conductor traversed by a current. Calling the length dl, and the current C, we have Cdl as the magnetic value of the element with respect to all points in its equatorial plan.

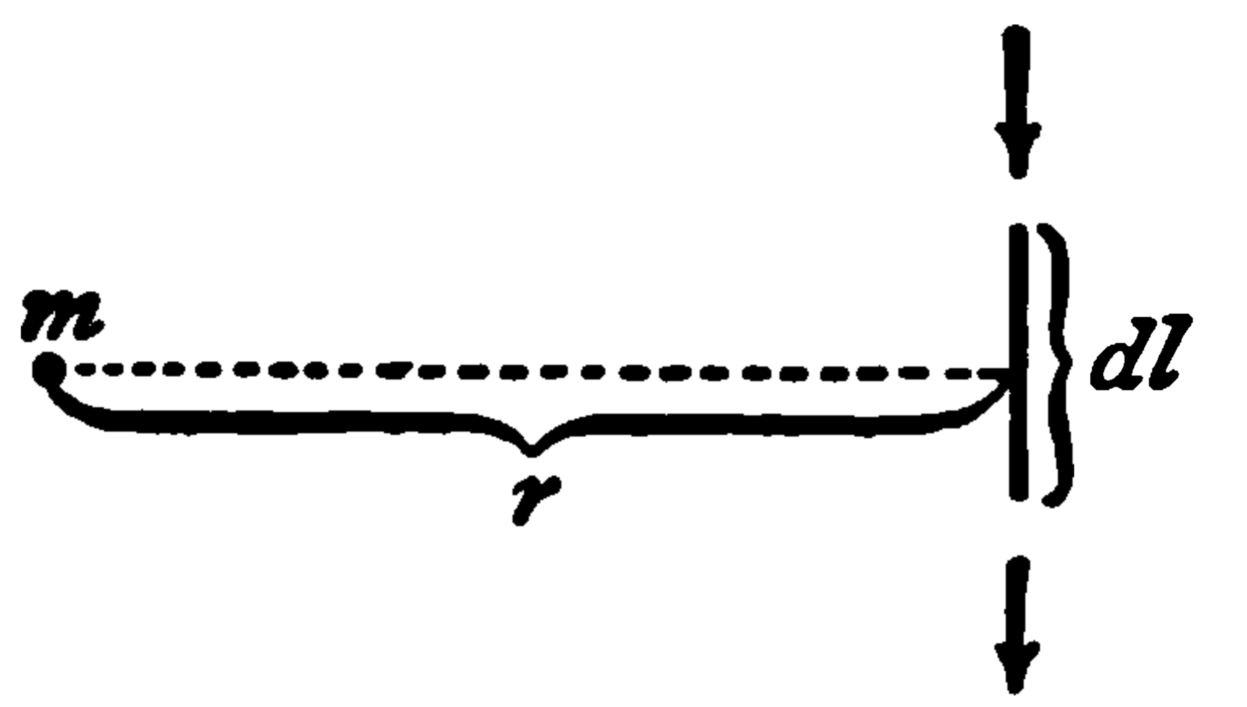


Fig. 173.

Suppose the element to be set (Fig. 173) at distance r from a magnet-pole of m units, and at right angles to the line joining them. Then, as the element is small compared with r, the law of inverse squares will hold good: the mutual force will be

$$f = \frac{m \cdot Cdl}{10 \cdot r^2}.$$

This will be neither an attraction nor a repulsion, but a force at right angles to the element and to the line joining it to m.

345. Magnetic Field due to Circular Current.—It is desired to find the effect of a circular current (Fig. 174) at any point on the axis, at a distance x from the centre. Suppose a unit-pole were placed at this point

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part acting at right angles to the axis, which will disappear by mutually cancelling out in pairs, and part acting in the line of the axis, which will for each element be equal to the above expression multiplied by sin θ. So that the elementary axial force due to each element of length dl will be

$$df = Cdl \cdot \sin\theta / 10\,a^2;$$

or, since $\sin\theta = y/a$,

$$df = Cdl \cdot y01 / a^3.$$

But the total force f due to all the elements will be the integral due to the sum of their lengths, and this integral length around the circle is $\int dl = 2\pi y$. Whence it at once follows that

$$f = 2\pi C y^2 / 10\,a^3.$$

Note that if P is pushed up to the centre of the circle $a = y$, and we get back to the rule for tangent galvanometer (Art. 212), $f = 2\pi C/10\,r$.

Also note that for very great distances of P from centre a becomes sensibly equal to x, the force varying inversely as the cube of the axial distance.

This affords one way of varying the sensitiveness of tangent galvanometers, the needle with its scale being arranged to slide out along the axis of the coil. At a point P, such that $a = 2y$, the force of coil on needle is only ⅛ of what it is at centre.

346. Moment of Circular Coil. — A circular coil carrying a current acts as a magnet whose axis is the axis of the coil. Its *magnetic moment* (Art. 135) will be the product of the current (in absolute units) into the area enclosed. Or, if C is in amperes, and A the total area of all the turns, its moment will be AC/10. If such a coil is placed in a field of intensity **H** it will tend to turn so as to place its axis along the direction of the field. If the angle between those directions is θ the torque (or turning-moment) will be $= ACH \sin\theta/10$.

347. Potential due to a Solenoidal or Circuital Distribution of Magnetism. — A long thin uniformly magnetized magnet exhibits poles only at the two ends, and acts on external objects just as if there were two equal quantities of opposite kinds of magnetism collected at these two points. Such a distribution of magnetism is sometimes called *solenoidal* or *circuital*. The magnetic potential due to a solenoid, and all its magnetic effects, depend only on the position of its two poles, and on their strength, and not on the form of the bar between them, whether straight or curved. In Art. 337 (c) was given the rule for finding the potential due to a system of poles. Suppose the two poles of a solenoid have strengths $+m$ and $-m$ respectively, and that the distances of these poles from an external point P are r_1 and r_2, then the potential at P will be

$$V_P = m\left(\frac{1}{r_1} - \frac{1}{r_2}\right).$$

Suppose a magnet curled round until its N and S poles touch one another: it will not act as a magnet on an external object, and will have no "field"; for if the two poles are in contact, their distances r_1 and r_2 to an external point P will be equal, and

$$\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \text{will be} = 0.$$

348. Potential due to a Magnetic Shell. — Gauss demonstrated that *the potential due to a magnetic shell at a point near it is equal to the strength of the shell multiplied by the solid-angle subtended by the shell at that point*; the "strength" of a magnetic shell being the product of its thickness into its surface-density of magnetization.

If ω represents the solid-angle subtended at the point P, and i the strength of the shell, then

$$V_P = \omega i.$$

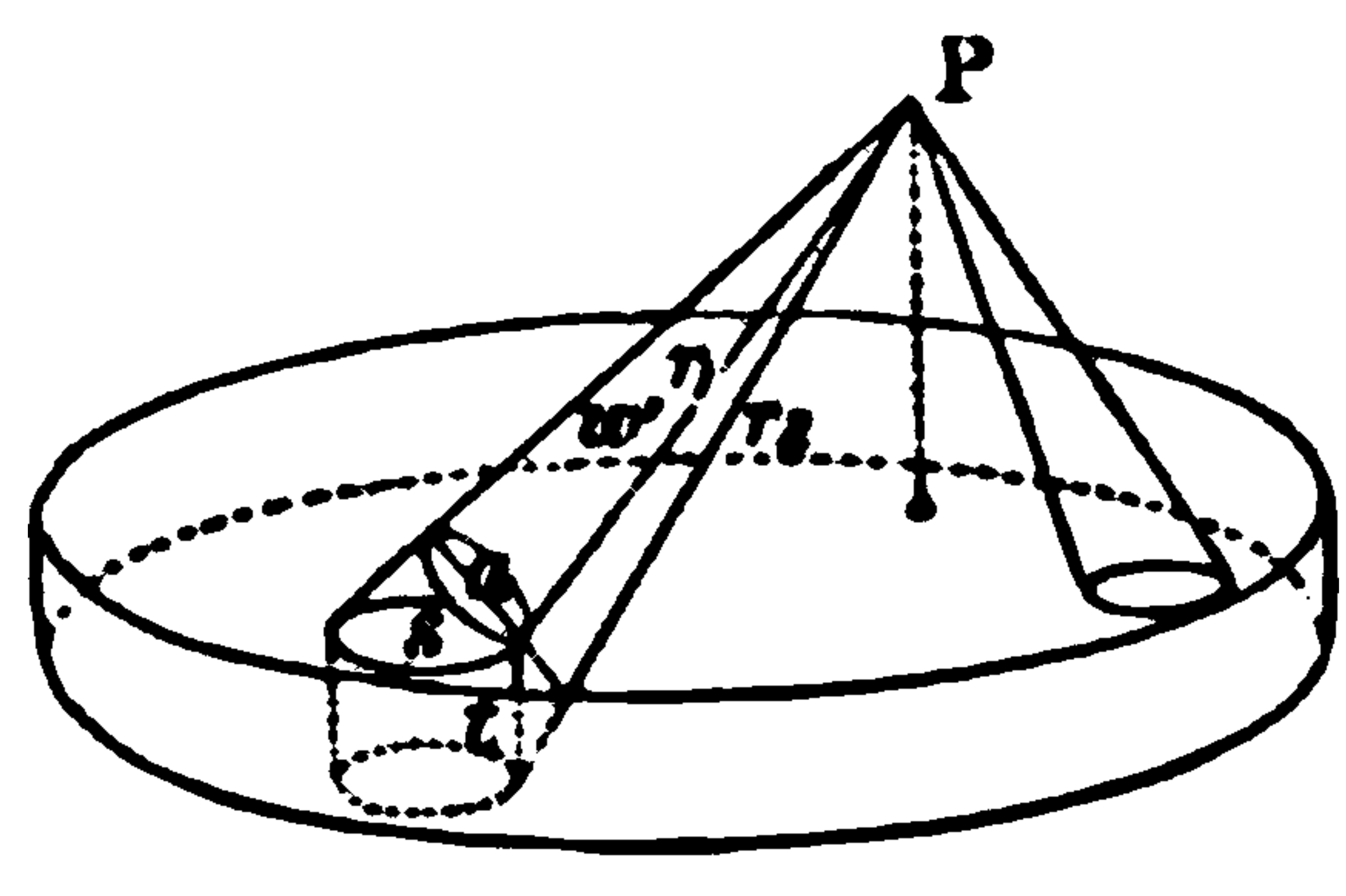


Fig. 175.

Proof. — To establish this proposition would require the integral calculus. But the following geometrical demonstration, though incomplete, must here suffice.

Let us consider the shell as composed, like that drawn, of a series of small elements of thickness t, and having each an area of surface s. The whole solid-angle subtended at P by the shell

may likewise be conceived as made up of a number of elementary small cones, each of solid-angle $\dot{\omega}$: Let r_1 and r_2 be the distances from P to the two faces of the element: Let a section be made across the small cone orthogonally, or at right angles to r_1, and call the area of this section a: Let the angle between the surfaces s and a be called angle β: then $s = a/\cos\beta$. Let i be the "strength" of the shell (*i.e.* = its surface-density of magnetism × its thickness); then i/t = surface-density of magnetism, and si/t = strength of either pole of the little magnet = m.

$$\text{Now solid-angle } \dot{\omega} = \frac{\text{area of its orthogonal section}}{r^2}$$

$$= a/r^2;$$

therefore $a = \dot{\omega}r^2,$

and $s = \dot{\omega}r^2/\cos\beta.$

Hence $\dot{\omega}ir^2/t\cos\beta = m.$

But the potential at P of the magnet whose pole is m will be

$$v = m\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

$$= \dot{\omega}i\frac{r^2}{t\cos\beta}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

but $\frac{1}{r_1} - \frac{1}{r_2} = \frac{r_2 - r_1}{r_1 r_2}$, which we may write $\frac{r_2 - r_1}{r^2}$

because r_1 and r_2 may be made as nearly equal as we please. And since $r_2 - r_1 = t\cos\beta$

$$v = \dot{\omega}i\frac{r^2}{t\cos\beta}\left(\frac{t\cos\beta}{r^2}\right)$$

$$v = \dot{\omega}i$$

or the potential due to the element of the shell = the strength of the shell × the solid-angle subtended by the element of the shell. Hence, if V be the sum of all the values of v for all the different elements, and if ω be the whole solid-angle (the sum of all the small solid-angles such as $\dot{\omega}$),

$$V_P = \omega i,$$

or the potential due to a magnetic shell at a point is equal to the strength of the shell multiplied by the solid-angle subtended by the whole of the shell at that point.

Hence ωi represents the work that would have to be done on or by a unit-pole, to bring it up from an infinite distance to the point P, where the shell subtends the solid-angle ω. At a point Q

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horizon, or half the whole space around the pole, the solid-angle* it subtended being therefore 2π, and the potential will be $+2\pi i$. If we had begun at the S-seeking face the potential at that face would be $-2\pi i$. It appears then that *the potential alters its value by $4\pi i$ on passing from one side of the shell to the other.*

There is a reaction between pole and shell similar to that (Art. 121) between pole and pole.

If a N-seeking pole be brought up to the N-seeking face of a shell none of the lines of force of the magnet will cut the shell, but will be repelled out as in Fig. 72; whereas if a N-seeking pole be brought up to the S-seeking face of a shell, large numbers of the lines will be run into one another; and the pole, as a matter of fact, will be attracted up to the shell, where as many lines of force as possible are cut by the shell. We may formulate this action by saying that *a magnetic shell and a magnet-pole* react on one another and *urge one another in such a direction as to make the number of lines of force that are cut by the shell a maximum* (Maxwell's Rule, Art. 204). Outside the attracting face of the shell the potential is $-\omega i$, and the pole moves so as to make this negative quantity as great as possible, or to make the potential a minimum. Which is but another way of putting the matter as a particular case of the general proposition that bodies tend to move so that the energy they possess in virtue of their position tends to run down to a minimum.

350. Magnetic Potential due to Current.—The propositions concerning magnetic shells given in the preceding paragraphs derive their great importance because of the fact laid down in Art. 203 that circuits, traversed by currents of electricity, behave like magnetic shells. Adopting the electromagnetic unit of current (Art. 353), we may at once go back to Art. 347, and take the theorems about magnetic shells as being also true of closed voltaic circuits.

(*a*) **Potential due to closed circuit** (compare Art. 348).

The potential V due to a closed voltaic circuit (traversed by a current) *at a point P near it, is equal to the strength of the current multiplied by the solid-angle ω subtended by the circuit at that point.* If C be the strength of the current in electromagnetic units, then

$$V_P = -\omega C.$$

(*b*) At a point Q, where the solid-angle subtended by the circuit is ω_Q instead of ω_P, the potential will have a different value, the difference of potential being

$$V_Q - V_P = -C(\omega_Q - \omega_P).$$

* See note on Ways of Reckoning Angles, Art. 144 and Appendix A.

(*c*) **Mutual Potential of a Magnet-pole and a Circuit.**—If a magnet-pole of strength m were brought up to P, m times as much work will be done as if the magnet-pole had been of unit strength, and the work would be just as great whether the pole m were brought up to the circuit, or the circuit up to the pole. Hence, the *mutual potential* will be

$$-m\omega C.$$

But, as in Art. 349, we may regard $m\omega$ as representing the number of lines of force of the pole which are intercepted by and pass through the circuit, and we may write N for that number, and say

$$V = -CN,$$

or *the mutual potential of a magnet-pole and a circuit is equal to the strength of the current multiplied by the number of the magnet-pole's lines of force that are intercepted by the circuit*, taken with reversed sign.

(*d*) As in the case of the magnetic shell, so with the circuit, the value of the potential changes by $4\pi C$ from a point on one side of the circuit to a point just on the other side; that is to say, being $-2\pi C$ on one side and $+2\pi C$ on the other side work equal to $4\pi C$ must be done in carrying a unit-pole from one side to the other round the outside of the circuit. The work done in thus threading the circuit along a path looped S times round it would be $4\pi SC$.

351. (*e*) **Mutual Potential of two Circuits.**—Two closed circuits will have a mutual potential, depending on the strengths of their respective currents, on their distance apart, and on their form and position. If their currents be respectively C and C', and if the distance between two elements ds and ds' of the circuits be called r, and ϵ the angle between the elements, it can be shown that their *mutual potential* is $= -CC'\int\int\frac{\cos\epsilon}{r}\,ds\,ds'$.
This expression represents the work that would have to be done to bring up either of the circuits from an infinite distance to its present position near the other, and is a negative quantity if they attract one another. Now, suppose the strength of current in each circuit to be unity; their mutual potential will in that case be $\int\int\frac{\cos\epsilon}{r}\,ds\,ds'$, a quantity which depends purely upon the geometrical form and position of the circuits, and for which we may substitute the single symbol M, which we will call the "*coefficient of mutual potential*": we may now write the mutual potential of the two circuits when the currents are C and C' as $= -CC'M$.

But we have seen in the case of a single circuit that we may represent the potential between a circuit and a unit-pole as the product of the strength of the current − C into the number N of the magnet-pole's lines of force intercepted by the circuit. Hence the symbol M must represent the number of each other's lines of force mutually intercepted by both circuits, if each carried unit current. If we call the two circuits A and B, then, when each carries unit current, A intercepts M lines of force belonging to B, and B intercepts M lines of force belonging to A.

Now suppose both currents to run in the same (clock-wise) direction; the front or S-seeking face of one circuit will be opposite to the back or N-seeking face of the other circuit, and they will attract one another, and will actually *do* work as they approach one another, or (as the negative sign shows) negative work will be done in bringing up one to the other. When they have attracted one another up as much as possible the circuits will coincide in direction and position as nearly as can ever be. Their potential energy will have run down to its lowest minimum, their mutual potential being a negative maximum, and their coefficient of mutual potential M, having its greatest possible value. *Two circuits*, then, *are urged so that their coefficient of mutual potential* M *shall have the greatest possible value.* This justifies Maxwell's Rule (Art. 204), because M represents the number of lines of force mutually intercepted by both circuits. And since in this position each circuit *induces* as many lines of magnetic force as possible through the other, the *coefficient of mutual potential* M is also called the *coefficient of mutual induction* (Art. 454).

Lesson XXVII.—*The Electromagnetic System of Units*

352. Magnetic Units.—All magnetic quantities, strength of poles, intensity of magnetization, etc., are expressed in terms of special units derived from the fundamental units of *length*, *mass*, and *time*, explained in the *Note on Fundamental and Derived Units* (Art. 280). Most of the following units have been directly explained in the preceding Lesson, or in Lesson XI.; the others follow from them.

Unit Magnet-pole.—The unit magnetic pole is one of such a strength, that when placed at a distance of 1 centimetre (in air) from a similar pole of equal strength, repels it with a force of 1 dyne (Art. 141).

Magnetic Potential.—Magnetic potential being measured by *work* done in moving a unit magnetic pole against the

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Unit of Quantity of Electricity is that quantity which is conveyed by unit current in one second.

Unit of Capacity.—Unit capacity requires unit quantity to charge it to unit potential.

Unit of Induction.—Unit induction is such that unit electromotive-force is induced by the variation of the current at the rate of one unit of current per second.

354. **Practical Units and Standards.***—Several of the above "absolute" units in the C.G.S. system would be inconveniently large and others inconveniently small for practical use. The following are therefore chosen as practical units:—

Resistance.—The **Ohm**, = 10^9 absolute units of resistance (and theoretically the resistance represented by the velocity of one earth-quadrant per second, see Art. 357), but actually represented by the resistance of a uniform column of mercury 106·3 centimetres long and 14·4521 grammes in mass, at 0° C. Such a column of mercury is represented by a "standard" ohm (see Appendix B).

Current.—The **Ampere** (formerly called the "weber"), = 10^{-1} absolute units; practically represented by the current which deposits silver at the rate of 0·001118 gramme per second (see Appendix B).

Electromotive-force.—The **Volt**, = 10^8 absolute units, is that E.M.F. which applied to 1 ohm will produce in it a current of 1 ampere; being $\frac{1000}{1434}$ of the E.M.F. of a Clark standard cell at 15° C. (See Appendix C.)

Quantity.—The **Coulomb**, = 10^{-1} absolute units of quantity; being the quantity of electricity conveyed by 1 ampere in one second.

Capacity.—The **Farad**, = 10^{-9} (or one one-thousand-millionth) of absolute unit of capacity; being the capacity of a condenser such as to be changed to a potential of 1 volt by 1 coulomb. The *microfarad* or millionth part of 1 farad = 10^{-15} absolute units.

Work.—The **Joule**, = 10^7 absolute units of work (ergs), is represented by energy expended in one second by 1 ampere in 1 ohm.

Power.—The **Watt**, = 10 absolute units of power (ergs per second), is power of a current of 1 ampere flowing

* The word "unit" expresses our conception in the abstract of a unit quantity, such as those defined in the preceding Articles. A "standard" is the concrete thing with which we compare quantities to be measured, such as a centimetre scale or a standard cell.

under a pressure of 1 volt. It is equal to 1 joule per second, and is approximately $\frac{1}{746}$ of one horse-power.

Induction.—The Henry, $= 10^9$ absolute units of induction, is the induction in a circuit when the electromotive-force induced in this circuit is 1 volt, while the inducing current varies at the rate of 1 ampere per second.

Seeing, however, that quantities a million times as great as some of these, and a million times as small as some, have to be measured by electricians, the prefixes **mega-** and **micro-** are sometimes used to signify respectively "one million" and "one-millionth part." Thus a *megohm* is a resistance of one million ohms, a *microfarad* a capacity of $\frac{1}{1000000}$ of a farad, etc. The prefix **kilo-** is used for "one thousand," and **milli-** for "one-thousandth part"; thus a *kilowatt* is 1000 watts, and *milliampere* is the thousandth part of 1 ampere.

The "practical" system may be regarded as a system of units derived not from the fundamental units of *centimetre*, *gramme*, and *second*, but from a system in which, while the unit of time remains the second, the units of length and mass are respectively the earth-quadrant and 10^{-11} gramme.

355. Use of Index Notation.—Seeing that electricians have to deal with quantities requiring in some cases very large numbers, and in other cases very small numbers, to express them, a system of *index notation* is adopted, in order to obviate the use of long rows of ciphers. In this system the significant figures only of a quantity are put down, the ciphers at the end, or (in the case of a long decimal) at the beginning, being indicated by an index written above. Accordingly, we may write a thousand $(= 10 \times 10 \times 10)$ as 10^3, and the quantity 42,000 may be written 42×10^3. The British National Debt of £770,000,000 may be written £77×10^7. Fractional quantities will have negative indices when written as exponents. Thus $\frac{1}{100}$ $(= 0{\cdot}01)$ $= 1 \div 10 \div 10 = 10^{-2}$. And so the decimal 0·00028 will be written 28×10^{-5} (being $= 28 \times {\cdot}00001$). The convenience of this method will be seen by an example or two on electricity. The electrostatic capacity of the earth is 630,000,000 times that of a sphere of one centimetre radius, $= 63 \times 10^7$ (electrostatic) units. The resistance of selenium is about 40,000,000,000, or 4×10^{10} times as great as that of copper; that of *air* is about 10^{26}, or

100,000,000,000,000,000,000,000,000

times as great. The velocity of light is about 30,000,000,000 centimetres per second, or 3×10^{10}.

356. Dimensions of Magnetic and Electromagnetic Units.

— The fundamental idea of "dimensions" is explained in Art. 284. A little consideration will enable the student to deduce for himself the following table: —

	Units.		Dimensions.
	(*Magnetic.*)		
m	Strength of pole / Quantity of magnetism	$= \sqrt{\text{force} \times (\text{distance})^2}$ =	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-1}$
V	Magnetic potential	= work ÷ strength of pole =	$M^{\frac{1}{2}} L^{\frac{1}{2}} T^{-1}$
H	Intensity of field	= force ÷ strength of pole =	$M^{\frac{1}{2}} L^{-\frac{1}{2}} T^{-1}$
N	Magnetic Flux	= intensity × area =	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-1}$
Z	Reluctance	= flux ÷ mag. potential =	L
	(*Electromagnetic.*)		
C	Current (strength)	= intensity of field × length =	$M^{\frac{1}{2}} L^{\frac{1}{2}} T^{-1}$
Q	Quantity	= current × time =	$M^{\frac{1}{2}} L^{\frac{1}{2}}$
V E	Potential Electromotive-force	= work ÷ quantity =	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-2}$
R	Resistance	= E.M.F. ÷ current =	LT^{-1}
K	Capacity	= quantity ÷ potential =	$L^{-1} T^2$
W	Power	= current × potential =	$ML^2 T^{-3}$
L M	Self-induction Mutual induction	= E.M.F. ÷ current per sec. =	L

357. Resistance expressed as a Velocity. — It will be seen, on reference to the above table of "Dimensions" of electromagnetic units, that the dimensions of resistance are given as LT^{-1}, which are the same dimensions (see Art. 284) as those of a velocity. Every resistance is capable of being expressed as a velocity. The following considerations may assist the student in forming a physical conception of this. Suppose we have a circuit composed of two horizontal rails (Fig. 176), CS and DT, 1 centim. apart, joined at CD, and completed by means of a sliding piece AB. Let this variable circuit be placed in a uniform magnetic field of unit intensity, the lines of force being directed vertically downwards through the circuit. If, now, the slider be moved along towards ST with a velocity of n centimetres per second, the number

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pivoted about a vertical axis, as in Fig. 177, was made to rotate very rapidly and uniformly. Such a ring in rotating cuts the lines of force of the earth's magnetism. The northern half of the ring, in moving from west toward east, will have (see Rule, Art. 225) an upward current induced in it, while the southern half, in crossing from east toward west, will have a downward current induced in it. Hence the rotating ring will, as it spins, act as its own galvanometer if a small magnet be hung at its middle; the magnetic effect due to the rotating coil being proportional directly to the horizontal component of the earth's magnetism, to the velocity of rotation, and to the number of turns of wire in the coil, and inversely proportional to the resistance of the wire of the coils. Hence, all the other data being known, the resistance can be calculated and measured *as a velocity*. The earliest *ohms* or *B.A. units* were constructed by comparison with this rotating coil; but there being some doubt as to whether the B.A. unit really represented 10^9 centims. per second, a redetermination of the ohm was suggested in 1880 by the British Association Committee. At the first International Congress of Electricians in Paris 1881, the project for a redetermination of the ohm was endorsed, and it was also agreed that the practical standards should no longer be constructed in German silver wire, but that they should be made upon the plan originally suggested by Siemens, by defining the *practical ohm* as the resistance of a column of pure mercury of a certain length, and of one millimetre of cross-section. The original "Siemens' unit" was a column of mercury one metre in length, and one square millimetre in section, and was rather less than an ohm (0·9540 B.A. unit). Acting on measurements made by leading physicists of Europe, the Paris Congress of 1884 decided that the mercury column representing the "*legal*" ohm should be 106 centimetres in length. This was, however, never legalized in this country or in America, as it was known to be incorrect. Lord Rayleigh's determination gave 106·21 centimetres of mercury, as representing the true theoretical ohm (= 10^9 absolute units); and Rowland's determinations at Baltimore

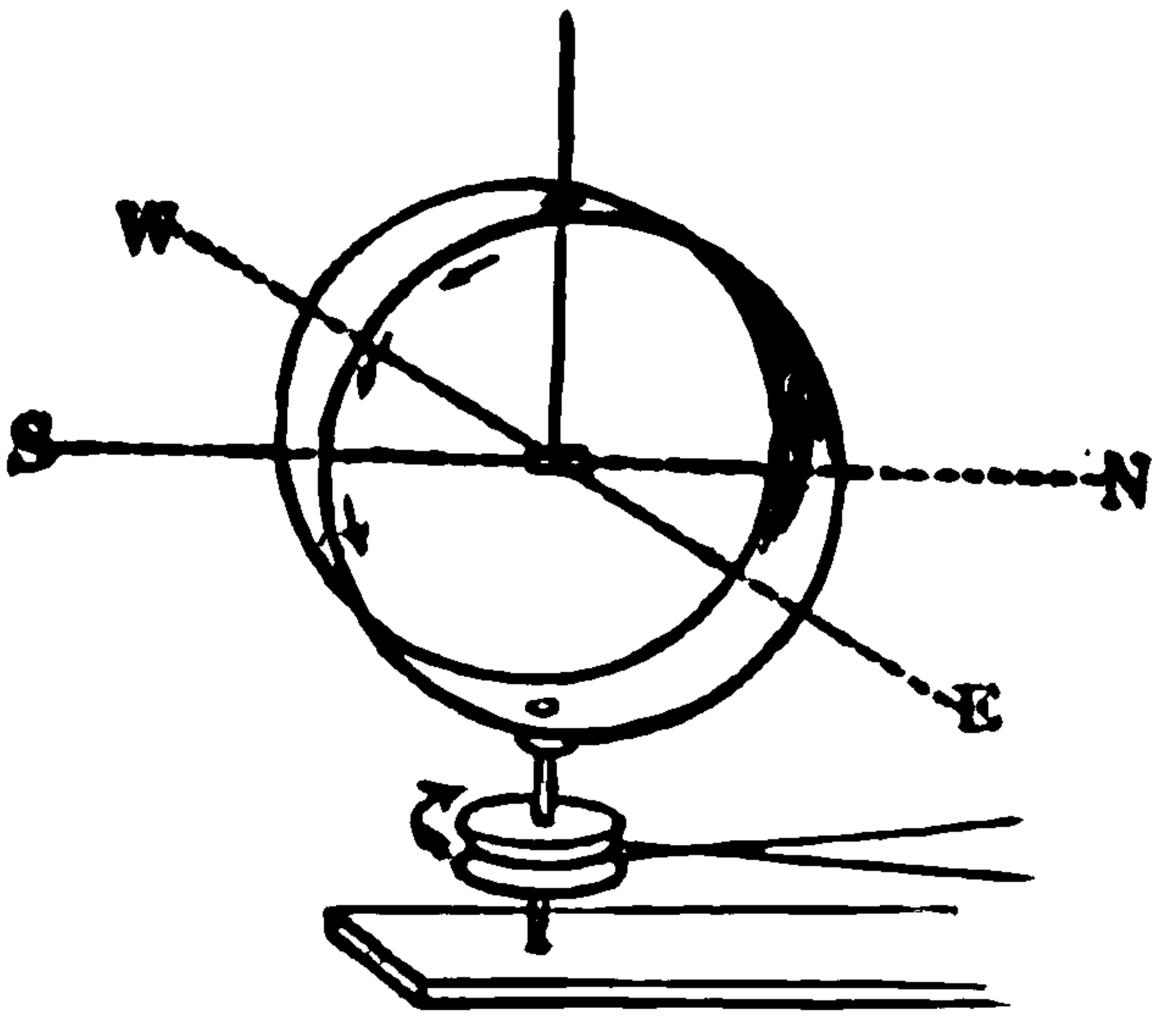


Fig. 177.

came slightly higher. The British Association Committee in 1892 agreed to lengthen it to 106·3 centims., and to define by mass instead of section. This was decided finally as the *international ohm* by the Congress of Chicago in 1893. These international units are now legalized in England and the United States. The bulletin issued by the U. S. Superintendent of Standard Weights and Measures, and endorsed by the Secretary of the U. S. Treasury, is given in abstract in Appendix B.

The old B.A. unit is only 0·9863 of the true ohm; the Siemens' unit is only 0·9408.

359. Ratio of the Electrostatic to the Electromagnetic Units. — If the student will compare the Table of Dimensions of Electrostatic Units of Art. 283 with that of the Dimensions of Electromagnetic Units of Art. 356, he will observe that the dimensions assigned to similar units are different in the two systems. Thus, the dimensions of "Quantity" in *electrostatic* measure are $M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-1}$, and in *electromagnetic* measure they are $M^{\frac{1}{2}} L^{\frac{1}{2}}$. Dividing the former by the latter we get LT^{-1}, a quantity which we at once see is of the nature of *a velocity*. This velocity occurs in every case in the ratio of the electrostatic to the electromagnetic measure of every unit. It is a definite concrete velocity, and represents that velocity at which two electrified particles must travel along side by side in order that their mutual electromagnetic attraction (considered as equivalent in so moving (Art. 397) to two parallel currents) shall just equal their mutual electrostatic repulsion (see Art. 260). This velocity, "v," which is of enormous importance in the *electromagnetic theory of light* (Art. 518), has been measured in several ways.

UNIT.	ELECTROSTATIC.	ELECTROMAGNETIC.	RATIO.
Quantity .	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-1}$	$M^{\frac{1}{2}} L^{\frac{1}{2}}$	$LT^{-1} = v$
Potential .	$M^{\frac{1}{2}} L^{\frac{1}{2}} T^{-1}$	$M^{\frac{1}{2}} L^{\frac{3}{2}} T^{-2}$	$L^{-1} T = 1/v$
Capacity .	L	$L^{-1} T^2$	$L^2 T^{-2} = v^2$
Resistance .	$L^{-1} T$	$L T^{-1}$	$L^{-2} T^2 = 1/v^2$

(*a*) Weber and Kohlrausch measured the electrostatic unit of quantity and compared it with the electromagnetic unit of quantity, and found the ratio v to be $= 3{\cdot}1074 \times 10^{10}$ centims. per second.

(*b*) Lord Kelvin compared the two units of potential and found

$$v = 2{\cdot}825 \times 10^{10},$$

and later, $= 2{\cdot}93 \times 10^{10}$.

(*c*) Professor Clerk Maxwell balanced a force of electrostatic attraction against one of electromagnetic repulsion, and found

$$v = 2{\cdot}88 \times 10^{10}.$$

(*d*) Professors Ayrton and Perry measured the capacity of a condenser electromagnetically by discharging it into a ballistic galvanometer, and electrostatically by calculations from its size, and found

$$v = 2{\cdot}980 \times 10^{10}.$$

The velocity of light according to latest values is —

$$= 2{\cdot}9992 \times 10^{10};$$

so we take v as 3×10^{10}, or *thirty thousand million centimetres per second.*

360. Rationalization of Dimensions of Units. — It seems absurd that there should be two different units of electricity; still more absurd that one unit should be thirty thousand million centimetres per second greater than the other. It also seems absurd that the dimensions of a unit of electricity should have fractional powers, since such quantities as $M^{\frac{1}{2}}$ and $L^{\frac{3}{2}}$ are meaningless. These irrational things arise from the neglect to take account of the properties of the medium in applying the law of inverse squares to form definitions of the unit of electricity in the electrostatic system, and of the unit-pole in the magnetic system. If we were to insert the dielectric constant k in the former, and the permeability μ in the latter, we might, if we knew the dimensions of these quantities, be able to rationalize the dimensional formulæ. But we do not know their dimensions. Rücker has, however, shown that they can be rationalized, and the two sets of units brought into agreement,* by assuming that the product $k\mu$ has the dimensions of the reciprocal of the square of a velocity: or $v = 1/\sqrt{k\mu}$. If k were the reciprocal of the rigidity of the ether, and μ its density, v would represent the velocity of propagation of waves in it. Compare Art. 518 on electromagnetic theory of light.

361. Earth's Magnetic Force in Absolute Units. — In making absolute determinations of current by the tangent galvanometer, or of electromotive-force by the spinning coil, it is needful to know the absolute value of the earth's magnetic field, or of its horizontal component. The intensity of the earth's magnetic force at any place is the force with which a magnet-pole of

* See Everett's *Units and Physical Constants*, 4th edition (1893), p. 208.

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tional to $\frac{M}{H}$, and inversely proportional to the *cube* of the distance r; or

$$\frac{M}{H} = r^3 \tan \delta.$$

Dividing the former equation by this, and taking the square root, we get

$$H = \frac{2\pi}{T}\sqrt{\frac{K}{r^3 \tan}}.$$

Lesson XXVIII. — *Properties of Iron and Steel*

362. Magnetization of Iron. — When a piece of magnetizable metal is placed in a magnetic field, some of the lines of magnetic force run through it and magnetize it. The intensity of its magnetization will depend upon the intensity of the field into which it is put and upon the metal itself. There are two ways of looking at the matter, each of which has its advantages. We may think about the internal condition of the piece of metal, and of the number of magnetic lines that are running through it and emerging from it into the surrounding space. This is the modern way. Or we may think of the magnetism of the iron or other metal as something resident on the polar surfaces, and expressed therefore in units of magnetism. This is the old way. The fact that soft iron placed in the magnetic field becomes highly magnetic may then be expressed in the following two ways: (1) when iron is placed in the magnetic field, the magnetic lines run in greater quantities through the space now occupied by iron, for iron is very *permeable* to the lines of magnetic induction, being a good conductor of the magnetic lines; (2) iron when placed in the magnetic field develops strong poles on its end-surfaces, being highly *susceptible* to magnetization. Each of these ideas may be rendered exact by the introduction of appropriate coefficients.

363. Permeability. — The precise notion now attached to this word is that of a numerical coefficient. Suppose a magnetic force — due, let us say, to the circulation of an electric current in a surrounding coil — were to

act on a space occupied by air, there would result a certain number of magnetic lines in that space. In fact, the intensity of the magnetic force, symbolized by the letter H, is often expressed by saying that it would produce H magnetic lines per square centimetre in air. Now, owing to the superior magnetic power of iron, if the space subjected to this magnetic force were filled with iron instead of air, there would be produced a larger number of magnetic lines per square centimetre. This larger number of magnetic lines in the iron expresses the degree of magnetization* in the iron; it is symbolized by the letter B. The ratio of B to H expresses the *permeability* of the material. The usual symbol for permeability is the Greek letter μ. So we may say that B is equal to μ times H, or

$$\mu = B/H.$$

For example, a certain specimen of iron, when subjected to a magnetic force capable of creating, in air, 50 magnetic lines to the square centimetre, was found to be permeated by no fewer than 16,062 magnetic lines per square centimetre. Dividing the latter figure by the former gives as the value of the permeability at this stage of the magnetization 321, or the permeability of the iron is 321 times that of air.

The permeability is always positive: for empty space it is 1, for air it is practically 1; for magnetic materials it is greater than 1, for diamagnetic materials it is slightly less than 1. In air, etc., B = H.

Where the magnetic lines emerge into the air at a polar surface they are of course continuous with the internal lines: the value of B just inside the polar surface is the same as that of B in the air just outside it.

The permeability of such non-magnetic materials as

* The actual number of magnetic lines that run through unit area of cross-section in the iron or other material—denoted by the symbol B—is called by several names—"the permeation," "the internal magnetization," or "the induction." The last name, unfortunately used by Maxwell and Hopkinson, is to be avoided. A better name is "flux density."

silk, cotton, and other insulators, also of brass, copper, and all the non-magnetic metals, is taken at 1, being practically the same as that of the air.

This mode of expressing the facts is, however, complicated by the fact of the tendency in all kinds of iron to magnetic saturation. In all kinds of iron the magnetizability of the material becomes diminished as the actual magnetization is pushed further. In other words, when a piece of iron has been magnetized up to a certain degree, it becomes, from that degree onward, less permeable to further magnetization, and though actual saturation is never reached, there is a practical limit beyond which it cannot well be pushed. Joule discovered this tendency to a limit. The practical limit of **B** in good wrought iron is about 20,000 lines per square centimetre, or in cast iron about 12,000. Using extraordinary magnetizing forces, Ewing has found it possible to increase **B** to 45,000, and Du Bois has reached 60,000 lines per square centimetre. Manganese steel is curiously non-magnetic: Hopkinson found 310 as the maximum B.

364. Curves of Magnetization.—A convenient mode of studying the magnetic facts respecting any particular brand of iron is to plot on a diagram the curve of magnetization—*i.e.* the curve in which the values, plotted horizontally, represent the magnetic force **H**, and the values plotted vertically those that correspond to the respective magnetization B. In Fig. 178, which is modified from the researches of Ewing, are given five curves relating to soft iron, hardened iron, annealed steel, bard-drawn steel, and glass-hard steel. It will be noticed that all these curves have the same general form, and that there are three stages. (1) For small values of **H** the values of

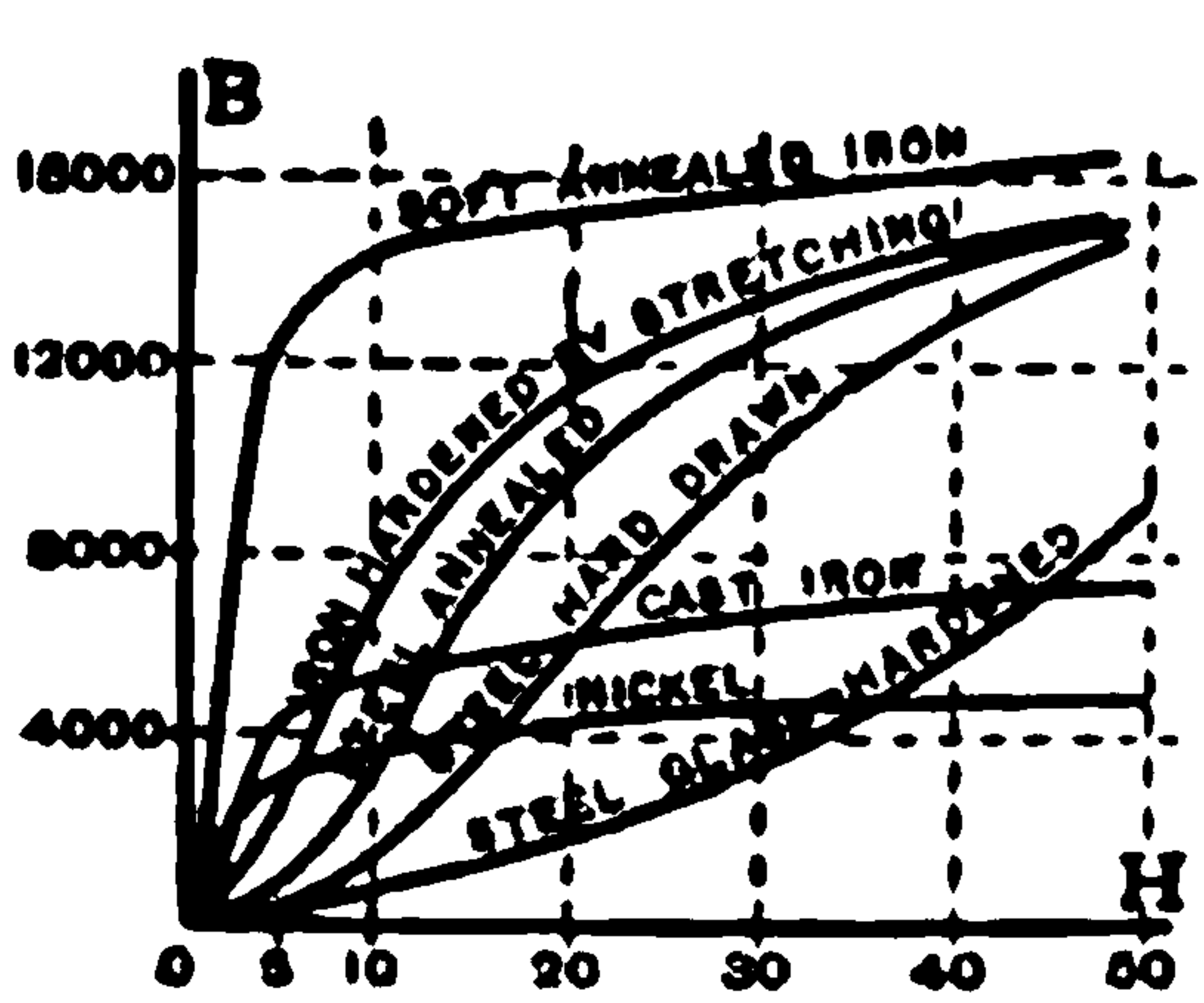


Fig. 178.

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tion, in moderately weak fields where H is less than about 5, the permeability has enormous values. But for values of H less than about 0·5 the permeability is quite small, usually about 300.

The three stages observed in the magnetization are explained in Ewing's molecular theory (Art. 127).

If iron is compressed its permeability decreases; if subjected to tensile stress it is increased, provided the field is not too intense. Villari found that beyond a certain intensity tension diminishes the permeability.

365. Susceptibility. — Suppose a magnet to have m units of magnetism on each pole; then if the length between its poles is l, the product ml is called its *magnetic moment*, and the magnetic moment divided by its volume is called its *intensity of magnetization;* this term being intended, though based on surface-unit of pole strength, to convey an idea as to the internal magnetic state. Seeing that volume is the product of sectional area into length, it follows that if any piece of iron or steel of uniform section had its surface magnetism situated on its ends only, its intensity of magnetization would be equal to the strength of pole divided by the area of end-surface. Writing I for the intensity of magnetization we should have

$$\mathrm{I} = \frac{\text{mag. moment}}{\text{volume}} = \frac{m \times l}{s \times l} = \frac{m}{s}.$$

Now, supposing this intensity of magnetization were due to the iron having been put into a magnetic field of intensity H, the ratio between the resulting intensity of magnetization I and the magnetizing force H producing it is expressible by a numerical coefficient of magnetization, or *susceptibility*, k. We may write

$$\mathrm{I} = k\mathrm{H},$$

$$\text{or} \qquad k = \mathrm{I}/\mathrm{H}.$$

This may be looked at as saying that for every

magnetic line in the field there will be k units of magnetism on the end-surface. In magnetic substances such as iron, steel, nickel, etc., the susceptibility k has positive values; but there are many substances such as bismuth, copper, mercury, etc., which possess feeble negative coefficients. These latter are termed "diamagnetic" bodies (Art. 369) and are apparently repelled by the poles of magnets. It was shown at end of Art. 338 that there are 4π magnetic lines proceeding from each unit of pole magnetism. Hence if, as shown above, each line of force of the magnetizing field produces k units of magnetism there will be $4\pi k$ lines added by the iron to each 1 line in the field, or the permeability of the iron μ is equal to $1 + 4\pi k$. It follows that $\mathbf{B} = \mathbf{H} + 4\pi k\mathbf{H}$. This shows that **B** may go on increasing as long as **H** is increased, having no true limit. But since k decreases as saturation sets in, the surface magnetization **I** (or $\mathbf{B} - \mathbf{H}$ to which it is proportional) may have a true limit. This maximum of $\mathbf{B} - \mathbf{H}$ appears to be about 21,360 in wrought iron, 15,580 in cast iron, and 5060 in nickel.

In the following table are given some figures from the researches of Bidwell on wrought iron.

H	k	I	μ	B
3·9	151·0	587	1899·1	7390
10·3	89·1	918	1121·4	11550
40·	30·7	1226	386·4	15460
115·	11·9	1370	150·7	17330
208·	7·0	1452	88·8	18470
427·	3·5	1504	45·3	19330
585·	2·6	1530	33·9	19820

Everett has calculated (from Gauss's observations) that the intensity of magnetization of the earth is only 0·0790, or only $\frac{1}{17800}$ of what it would be if the globe

were wholly iron. In weak magnetic fields the susceptibility of nickel exceeds by about five times that of iron; but in strong fields iron is more susceptible.

366. Measurement of Permeability. — There are several ways of measuring the permeability of iron: they all involve a measurement of B.

(*a*) *Magnetometer Methods.* — The pole strength of long bars, when magnetized by a coil around them, can be measured by a magnetometer (Art. 138), and from this N is found by multiplying by 4π.

(*b*) *Induction Methods.* — Rings of iron which, having no poles, cannot be measured by the magnetometer are measured inductively. Upon the ring is wound a magnetizing coil, and also an exploring coil (Art. 232) which is connected to a ballistic galvanometer. On turning on or off the magnetizing current, or reversing it, induced currents are generated, giving a throw in the galvanometer proportional to the number of magnetic lines which have been made or destroyed. Iron rods can be examined by the same means.

(*c*) *Traction Methods.* — The pull needed to separate the two halves of a divided rod, or divided ring, is (Art. 384) proportional to the *square* of B. Bidwell and others have used this for measuring permeability.

(*d*) *Optical Methods.* — Du Bois has used a method based on Kerr's discovery (Art. 527) of magneto-optic rotation.

367. Residual Effects. — The retention of magnetism by steel, lodestone, hard iron, and even by soft iron if of elongated shape, has been already described (Art. 98). Some other residual effects must now be noted. It is found that if a new piece of iron or steel is subjected to an increasing magnetizing force, and then the magnetizing force is decreased to zero, some magnetism remains. If the results are plotted out in a curve it exhibits the following peculiarities. On first gradually increasing H from *o*, B rises as we have seen in Art. 364.

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of Hysteresis to the subject of the lag of magnetic effects behind their causes. From his researches* also is taken the case of Fig. 180, a specimen of soft iron, the curve for which shows various loops. Ewing has devised a *curve-tracer* for recording the curves automatically. The waste of energy per cubic centimetre in a cycle of strong magnetization may vary from 9000 ergs in annealed iron to 200,000 in glass-hard steel. If (as in the iron cores of alternate current transformers) the cycle is repeated 100 times a second the waste of power by hysteresis may heat the iron; and it increases greatly with the frequency and with the degree to which the magnetization is pushed. If B does not exceed 5000, the power wasted at 100 cycles per second in every cubic foot of iron may be as low as 575 watts, but if B is increased to 10,000 the waste becomes 1560 watts.

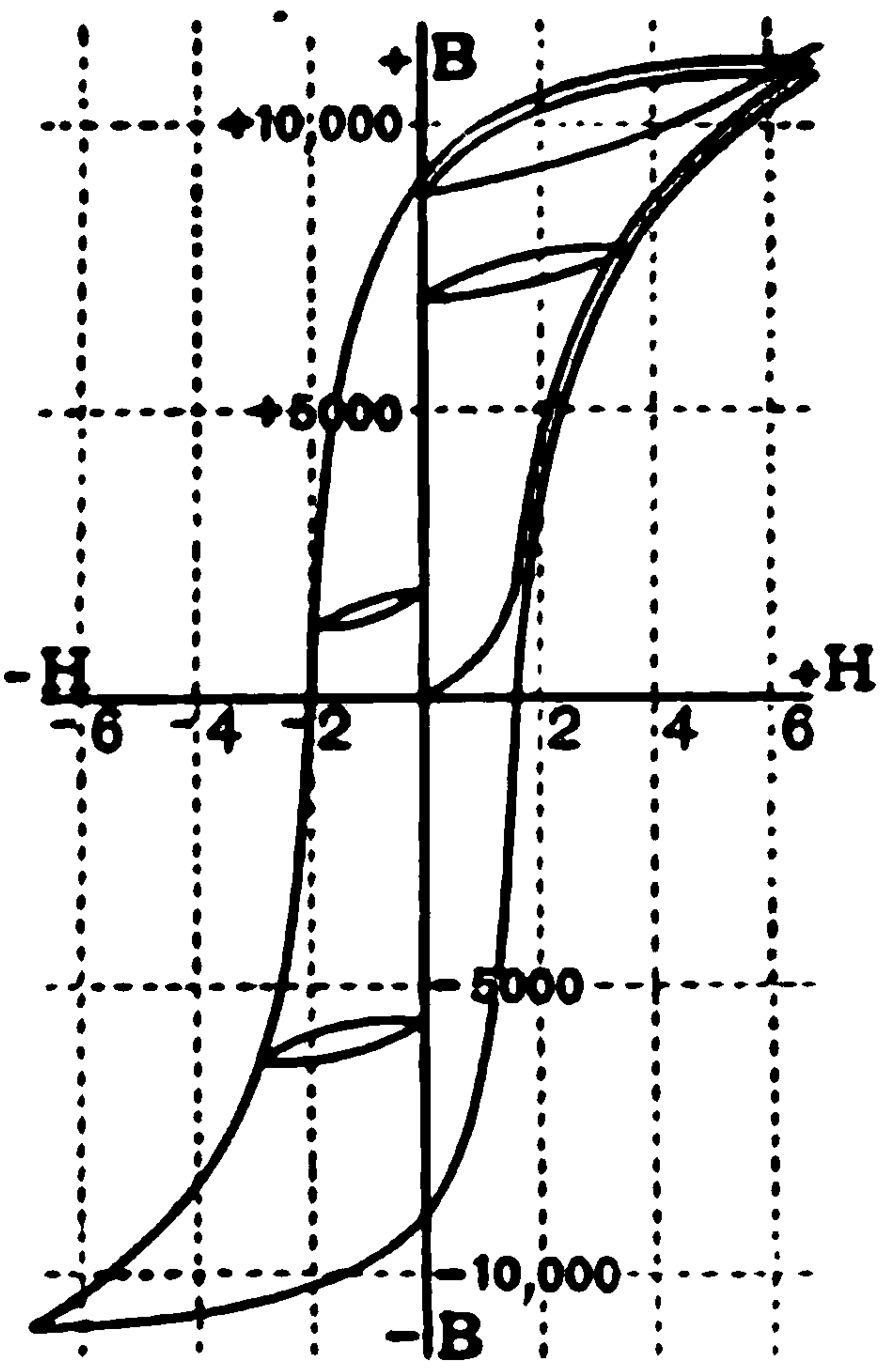


Fig. 180.

Since a smaller reversed force suffices to destroy magnetization than was required to produce it, all that is necessary in order to completely demagnetize iron is to subject it to a series of cycles of diminishing intensity.

Mechanical agitation tends to help the magnetizing forces to act, and lessens all residual and hysteresial effects.

Ewing has also shown that under constant magnetizing

* The student should not fail to consult Ewing's book, *Magnetic Induction in Iron.*

force the magnetism will go on slowly and slightly increasing for a long time: this is called magnetic *creeping*, or *viscous hysteresis*.

LESSON XXIX. — *Diamagnetism*

369. Diamagnetic Experiments. — In 1778 Brugmans of Leyden observed that when a lump of bismuth was held near either pole of a magnet needle it repelled it. In 1827 Le Baillif and Becquerel observed that the metal antimony also could repel and be repelled by the pole of a magnet. In 1845 Faraday, using powerful electromagnets, examined the magnetic properties of a large number of substances, and found that whilst a great many are, like iron, attracted to a magnet, others are feebly repelled. To distinguish between these two classes of bodies, he termed those which are attracted **paramagnetic**,* and those which are repelled **diamagnetic**. The property of being thus apparently repelled from a magnet he termed **diamagnetism**.

Faraday's method of experiment consisted in suspending a small bar of the substance in a powerful magnetic field between the two poles of an electromagnet, and observing whether the small bar was attracted into an **axial** position, as in Fig. 181, with its length along the line joining the two poles, or whether it was repelled into an **equatorial** position, at right angles to the line joining the poles, across the lines of force of the field, as is shown by the position of the small bar in Fig. 182, suspended between the poles of an electromagnet constructed on Ruhmkorff's pattern.

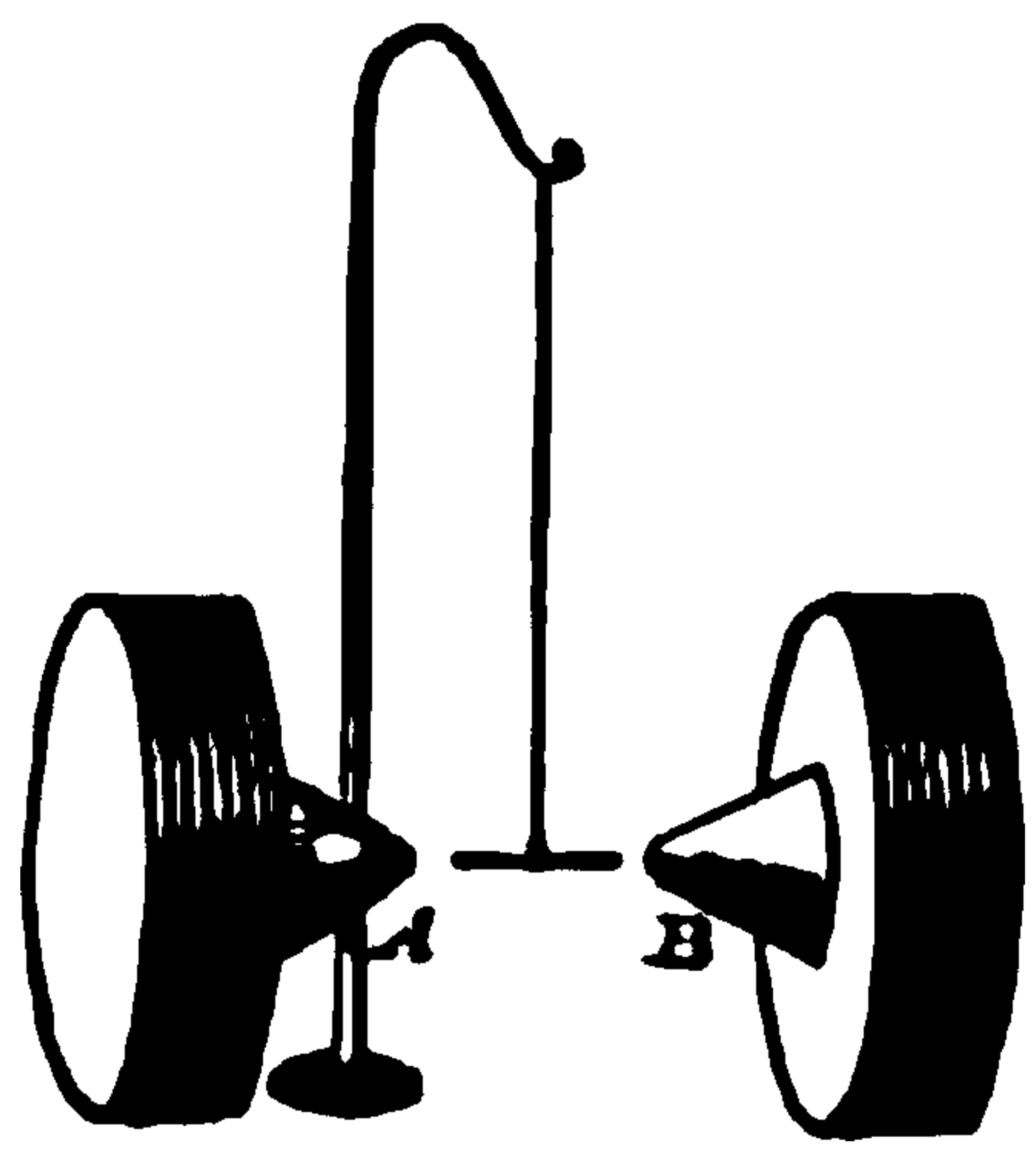


Fig. 181.

* Or simply "magnetic." Some authorities use the term "ferromagnetic."

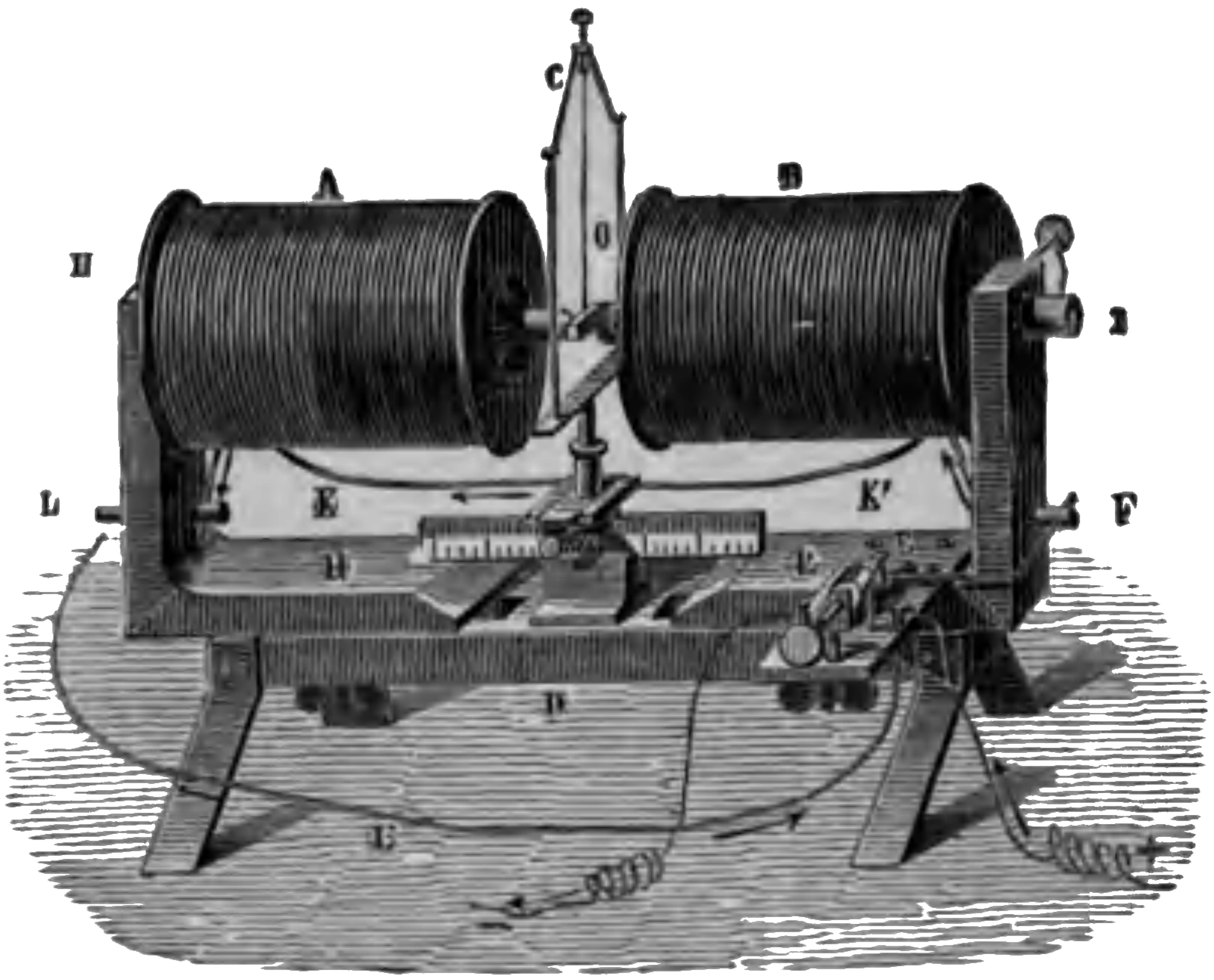


Fig. 182.

370. Results. — The following are the principal substances examined by the method: —

Paramagnetic.	Diamagnetic.
Iron	Bismuth
Nickel	Phosphorus
Cobalt	Antimony
Manganese	Thallium
Chromium	Zinc
Cerium	Mercury
Titanium	Lead
Platinum *	Silver
Many ores and salts containing the above metals	Copper
	Gold
	Water
Oxygen gas	Alcohol
Oxygen liquid	Tellurium
Ozone	Sulphur

* Chemically pure Platinum is *diamagnetic*, according to Wiedemann.

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A balloon, though it possesses mass and weight, rises through the air in obedience to the law of gravity, because the medium surrounding it is more attracted than it is. But it is found that diamagnetic repulsion takes place even in a vacuum: hence it would appear that the ether of space itself is more magnetic than the substances classed as diamagnetic.

372. Diamagnetic Polarity. — At one time Faraday thought that diamagnetic repulsion could be explained on the supposition that there existed a "diamagnetic polarity" the reverse of the ordinary magnetic polarity. According to this view, which, however, Faraday himself quite abandoned, a magnet, when its N pole is presented to the end of a bar of bismuth, induces in that end a N pole (the reverse of what it would induce in a bar of iron or other magnetic metal), and therefore repels it. Weber adopted this view, and Tyndall warmly advocated it, especially after discovering that the repelling diamagnetic force varies as the *square* of the magnetic power employed. It has even been suggested that when a diamagnetic bar lies equatorially across a field of force, its east and west poles possess different properties. The experiments named above suggest, however, an explanation less difficult to reconcile with the facts. It has been pointed out (Art. 363) that the degree to which magnetization goes on in a medium depends upon the magnetic permeability of that medium. Now, permeability expresses the number of magnetic lines induced in the medium for every line of magnetizing force applied. A certain magnetizing force applied to a space containing air or vacuum would induce a certain number of magnetic lines through it. If the space considered were occupied by a paramagnetic substance it would concentrate the magnetic lines into itself, as the sphere does in Fig. 183. But if the sphere were of a permeability less than 1, the magnetic lines would tend rather to pass through the air, as in Fig. 184. If the space considered were occupied by

bismuth, the same magnetizing force would induce in the bismuth *fewer* magnetic lines than in a vacuum. But those lines which were induced would still run in the same general *direction* as in the vacuum; *not in the opposite direction*, as Weber and Tyndall maintained. The result of there being a less induction through diamagnetic substances can be shown to be that such substances will be urged from places where the magnetic force is strong to places where it is weaker. This is why a ball of bismuth moves away from a magnet, and why a little bar of bismuth between the conical poles of the electromagnet (Fig. 182) turns equatorially so as to put its ends into the regions that are magnetically weaker. There is no reason to doubt that in a magnetic field of *uniform* strength a bar of bismuth would point along the lines of induction.

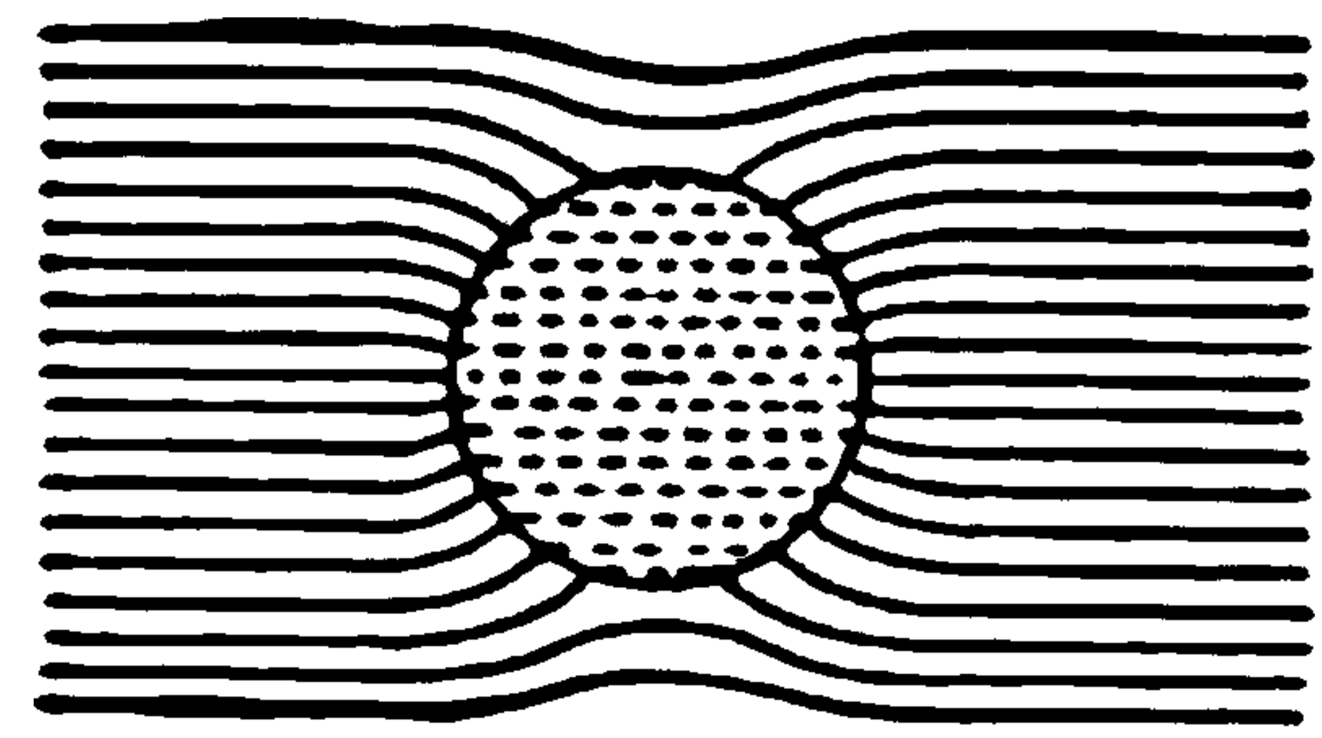


Fig. 183.

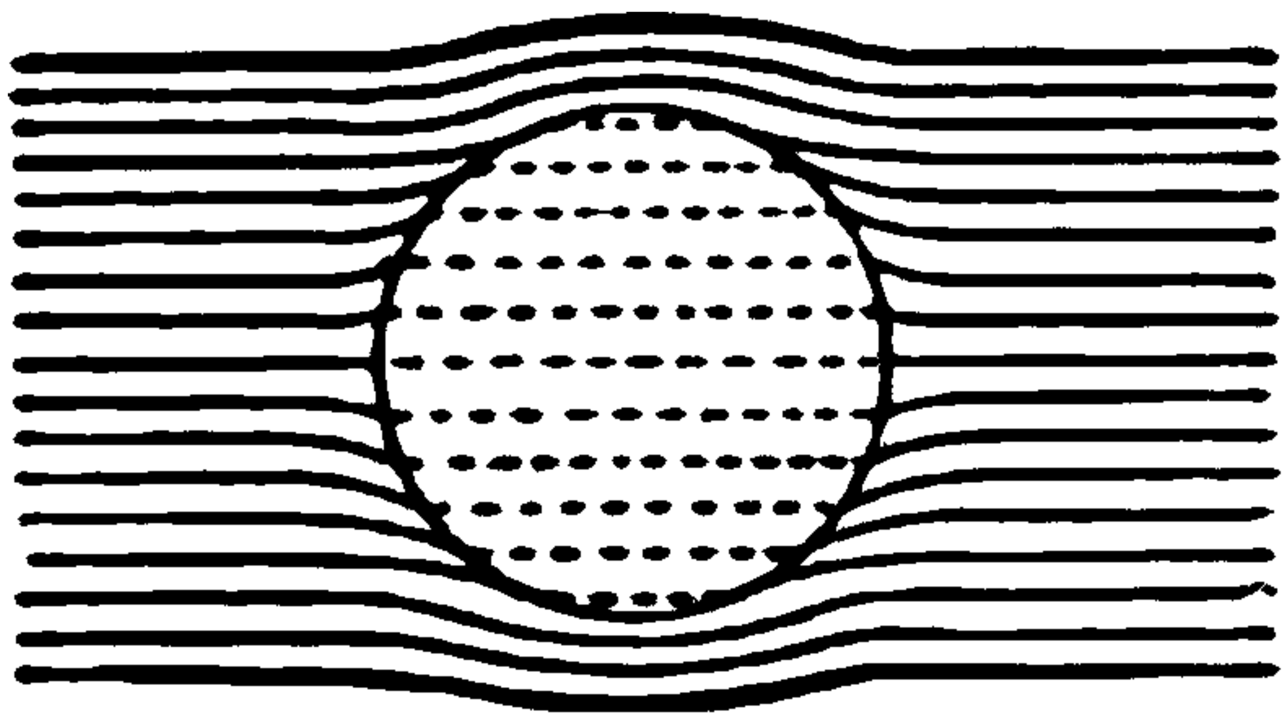


Fig. 184.

373. Magne-Crystallic Action.—In 1822 Poisson predicted that a body possessing crystalline structure would, if magnetic at all, have different magnetic powers in different directions. In 1847 Plücker discovered that a piece of tourmaline, which is itself feebly paramagnetic, behaved as a diamagnetic body when so hung that the axis of the crystal was horizontal. Faraday, repeating the experiment with a crystal of bismuth, found that it tended to point with its axis of crystallization along the lines of the field axially. The magnetic force acting thus upon crystals by virtue of their possessing a certain structure he named *magne-crystallic force.* Plücker endeavoured to connect the magne-crystallic behaviour of crystals with their optical behaviour, giving the following

law: there will be either repulsion *or* attraction of the optic axis (or, in the case of bi-axial crystals, of *both* optic axes) by the poles of a magnet; and if the crystal is a "negative" one (*i.e.* optically negative, having an extraordinary index of refraction *less* than its ordinary index) there will be repulsion, if a "positive" one there will be attraction. Tyndall has endeavoured to show that this law is insufficient in not taking into account the paramagnetic or diamagnetic powers of the substance as a whole. He finds that the magne-crystallic axis of bodies is in general *an axis of greatest density, and that if the mass itself be paramagnetic this axis will point axially; if diamagnetic, equatorially.* In bodies which, like slate and many crystals, possess cleavage, the planes of cleavage are usually at right angles to the magne-crystallic axis. Another way of stating the facts is to say that in non-isotropic bodies the induced magnetic lines do not necessarily run in the same direction as the lines of the impressed magnetic field.

374. Diamagnetism of Flames.—In 1847 Bancalari discovered that flames are repelled from the axial line joining the poles of an electromagnet. Faraday showed that all kinds of flames, as well as ascending streams of hot air and of smoke, are acted on by the magnet, and tend to move from places where the magnetic forces are strong to those where they are weaker. Gases (except oxygen and ozone), and hot gases especially, are feebly diamagnetic. But the active repulsion and turning aside of flames may possibly be in part due to an electromagnetic action like that which the magnet exercises on the convexion-current of the voltaic arc (Art. 448) and on other convexion-currents. The electric properties of flame are mentioned in Arts. 8 and 314.

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will be proportional directly to l, and inversely to A and μ. Calling the reluctance Z we have

$$Z = l/A\mu.$$

Example.—An iron bar 100 cm. long and 4 sq. cms. in cross-section is magnetized to such a degree that $\mu = 320$: then Z will be 0·078.

The reluctance of a magnetic circuit is generally made up of a number of reluctances in series. We will first take the case of a closed magnetic circuit (Fig. 185) made up of a curved iron core of length l_1, section A_1, and permeability μ_1; and an armature of length l_2, section A_2, and permeability μ_2, in contact with the ends of the former. In this case the reluctance is

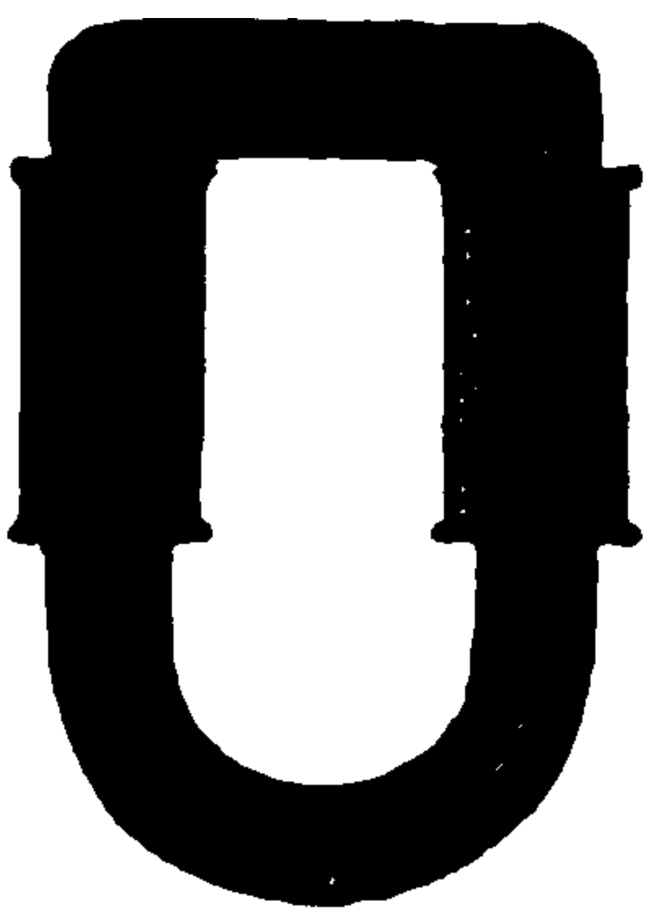


Fig. 185.

$$Z = \frac{l_1}{A_1\mu_1} + \frac{l_2}{A_2\mu_2}.$$

377. Calculation of Exciting Power.—

Passing on to the more difficult case of a circuit made up partly of iron and partly of air, we will suppose the armature to be moved to a distance, so that there are two air-gaps in the circuit, each gap of length l_3 (from iron to iron), and section A_3 (equal to area of pole face). This will introduce an additional reluctance $2l_3/A_3$, the permeability for air being $= 1$. It will also have the effect of making part of the magnetic flux leak out of the circuit.

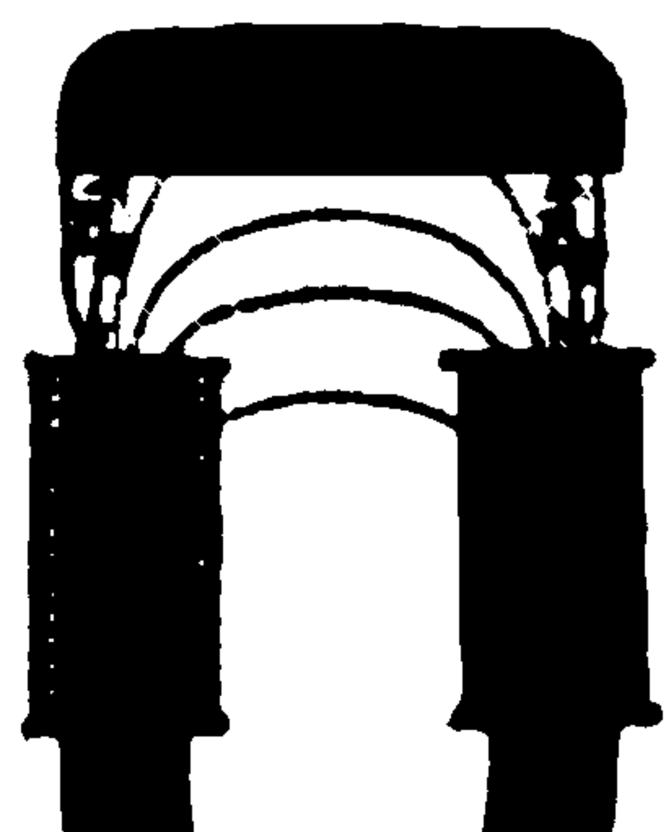


Fig. 186.

By Art. 341, if the exciting power consists of C amperes circulating in S spirals around the core, the magneto-motive-force will be $4\pi CS/10$. Applying this to the preceding example, dividing the magneto-motive-force by the reluctance, we get for the magnetic flux—

$$\mathbf{N} = \frac{4\pi CS}{10\left\{\dfrac{l_1}{A_1\mu_1} + \dfrac{l_2}{A_2\mu_2} + \dfrac{2l_3}{A_3}\right\}}$$

But more often the calculation is wanted the other way round, to find how many ampere-turns of excitation will be needed to produce a given flux through a magnetic circuit of given size. Two difficulties arise here. The permeability will depend on the degree of saturation. Also the leakage introduces an error. To meet the first difficulty approximate values of μ must be found. Suppose, for example, it was intended to produce a flux of 1,000,000 lines through an iron bar having a section of 80 sq. centims., then **B** will be 12,500, and reference to the table in Art. 364 shows that if the bar is of wrought iron μ will be about 1247. To meet the second difficulty we must estimate (from experience) an allowance for leakage. Suppose we find that of all the lines created in the U-shaped part only the fraction $1/\nu$ gets through the armature, then to force N lines through the armature we must generate ν**N** lines in the U-shaped piece, where ν is the coefficient of allowance for leakage, an improper fraction increasing with the width of the gaps.

We then proceed to calculate in parts as follows:—

Ampere-turns needed to drive **N** lines through iron of armature. $\Big\} = \mathbf{N} \times \dfrac{l_1}{A_1\mu_1} \div 1{\cdot}257.$

Ampere-turns needed to drive **N** lines through two gaps. $\Big\} = \mathbf{N} \times \dfrac{2l_3}{A_3} \div 1{\cdot}257$

Ampere-turns needed to drive ν**N** lines through iron of magnet core. $\Big\} = \nu\mathbf{N} \times \dfrac{l_2}{A_2\mu_2} \div 1{\cdot}257.$

Then adding up, we get:—

$$\text{Total ampere-turns needed} = \mathbf{N}\left\{\frac{l_1}{A_1\mu_1} + \frac{\nu l_2}{A_2\mu_2} + \frac{2l_3}{A_3}\right\} \div 1{\cdot}257.$$

Formulæ similar to this have been used by Hopkinson and by Kapp in designing electromagnets for dynamos.

378. Effect of Air-Gap in Circuit.—Air having no

remanence the presence of a gap in the iron circuit tends to make residual magnetism unstable, as though the polar magnetism on the end-faces had a self-demagnetizing effect. In fact it is very difficult to give a permanent magnetism to short pieces of metal. Further, the low permeability of air necessitates enormous magnetomotive-forces, compared with those required for iron, to produce a given flux. The effect is to shear over to the right the curves of magnetization, seeing that a greater H is needed to attain an equal value of B. Joints in the magnetic circuit have the same kind of effect.

The reason why the pull exerted by an electromagnet on its armature falls off so very greatly when the armature is moved away to a short distance is the diminution of the magnetic flux caused by the great reluctance of the air-gap thus introduced into the circuit.

379. General Law of Electromagnetic Systems. — Consider an electromagnetic system consisting of any number of parts — iron masses, coils carrying currents, air, masses of other materials, whether magnetic or diamagnetic — in any given configuration. Any change in the configuration of the parts will in general produce either an increase or a decrease in the magnetic flux. For example, if the armature of an electromagnet is allowed to move up toward the poles, or the needle of a galvanometer is allowed to turn, there will be a betterment of the magnetic circuit, and the magnetic flux through the coils will be increased. Magnetic circuits always tend to close up and become as compact as possible. On the contrary, if we pull away the armature from an electromagnet the magnetic reluctance is increased, and the flux diminished; and this action is resisted by the reaction of the system. All these things may be summed up in the following general law: —

Every electromagnetic system tends so to change the configuration of its parts as to make the magnetic flux a maximum.

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where Y represents the maximum number of magnetic lines that there would be if the magnetizing current were indefinitely increased and the iron core saturated, and C' stands for that number of amperes which would bring the magnetism up to half-saturation.

None of these empirical formulæ are as useful as the rational formula at the end of Art. 377.

Lesson XXXI. — *Electromagnets*

381. Electromagnets. — In 1820, almost immediately after Oersted's discovery of the action of the electric current on a magnet needle, Arago and Davy independently discovered how to magnetize iron and steel by inserting needles or strips into spiral coils of copper wire around

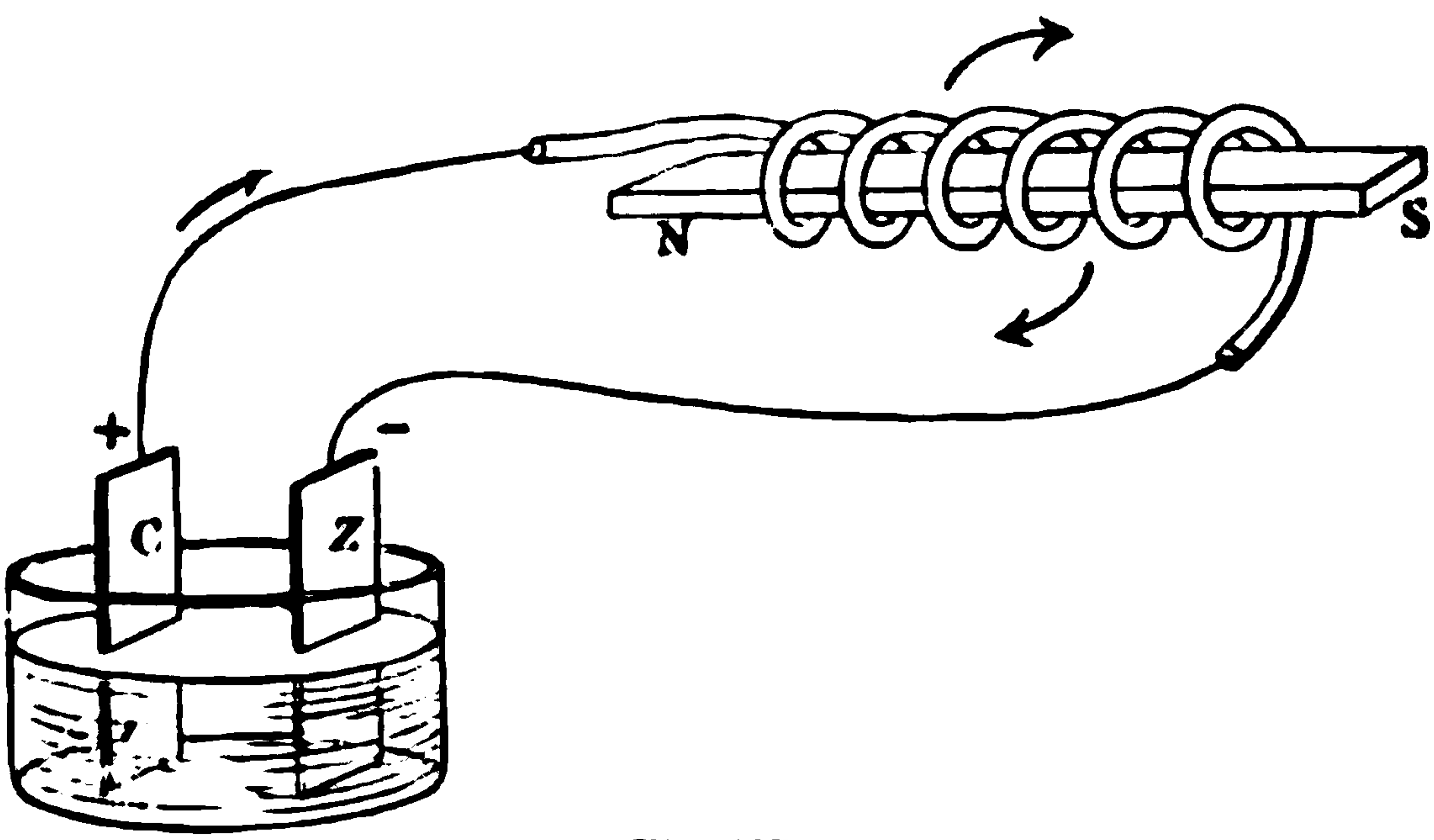


Fig. 187.

which a current was circulating. The method is shown in the simple diagram of Fig. 187, where a current from a single cell is passed through a spiral coil of insulated copper wire, in the hollow of which is placed a strip of iron or steel, which is thereby magnetized. The separate turns of the coil must not touch one another or the central bar, otherwise the current will take the shortest road open to it and will not traverse the whole of the coils. To prevent such short-circuiting by contact the

wire of the coil should be overspun with silk or cotton (in the latter case insulation is improved by varnishing it or by steeping the cotton covering in melted paraffin wax), or covered with a layer of guttapercha. If the bar be of iron it will be a magnet only so long as the current flows; and an iron bar thus surrounded with a coil of wire for the purpose of magnetizing it by an electric current is called an **Electromagnet**. Sturgeon, who gave this name, applied the discoveries of Davy and Arago to the construction of electromagnets far more powerful than any magnets previously made. His first electromagnet was a horse-shoe (Fig. 188) made of a rod of iron about 1 foot long and ½ inch in diameter coiled with a single stout copper wire of only 18 turns. With the current from a single cell it lifted 9 lbs.; but with a more powerful battery it lifted 50 lbs. It was first shown by Henry that when electromagnets are required to work at the distant end of a long line they must be wound with many turns of fine wire. The great usefulness of the electromagnet in its application to electric bells and telegraphic instruments lies in the fact that *its magnetism is under the control of the current;* when circuit is "made" it becomes a magnet, when circuit is "broken" it ceases to act as a magnet. Moreover, it is capable of being controlled from a distance, the current being "made" or "broken" at a distant point of the circuit by a suitable key or "switch."

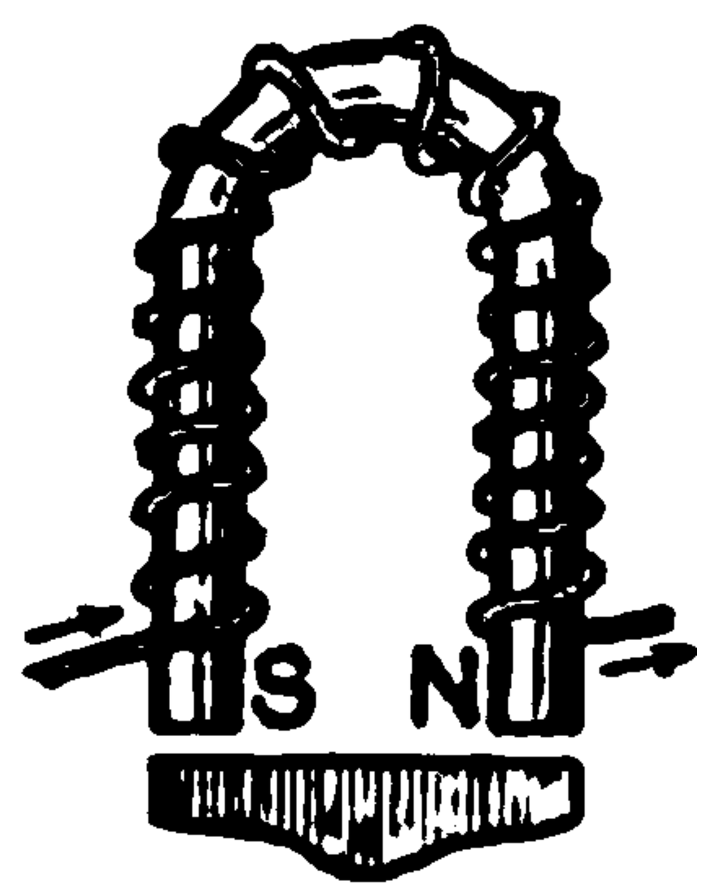


Fig. 188.

382. Polarity and Circulation of Current. — By applying Ampère's Rule (Art. 197) we can find which end of an electromagnet will be the N-seeking pole; for, imagining ourselves to be swimming in the current (Fig. 187), and to face towards the centre where the iron bar is, the N-seeking pole will be on the left. It is convenient to remember this relation by the following rules: —*Looking at the S-seeking pole of an electromagnet, the*

magnetizing currents are circulating round it in the same cyclic direction as the hands of a clock move; and, *looking at the N-seeking pole of an electromagnet, the magnetizing currents are circulating round it in the opposite cyclic direction to that of the hands of a clock.* Fig. 189 shows this graphically. These rules are true, no matter whether the beginning of the coils is at the end near the observer, or at the farther end from him, *i.e.* whether the spiral be a right-handed screw, or (as in Fig. 187) a left-handed screw. It will be just the same thing, so far as the magnetizing power is concerned, if the coils begin at one end and run to the other and back to where they began; or they may begin half-way along the bar and run to one end and then back to the other: the one important thing to know is which way the current flows round the bar when you look at it end-on. The corkscrew rule (Art. 198) leads to the same result.

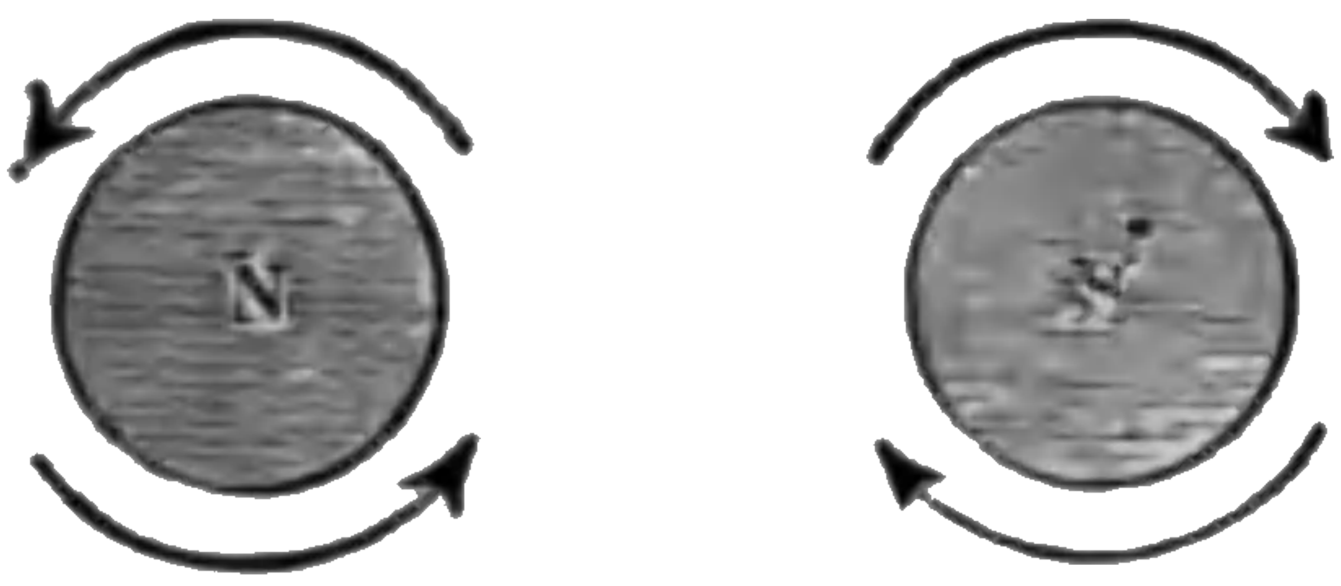


Fig. 189.

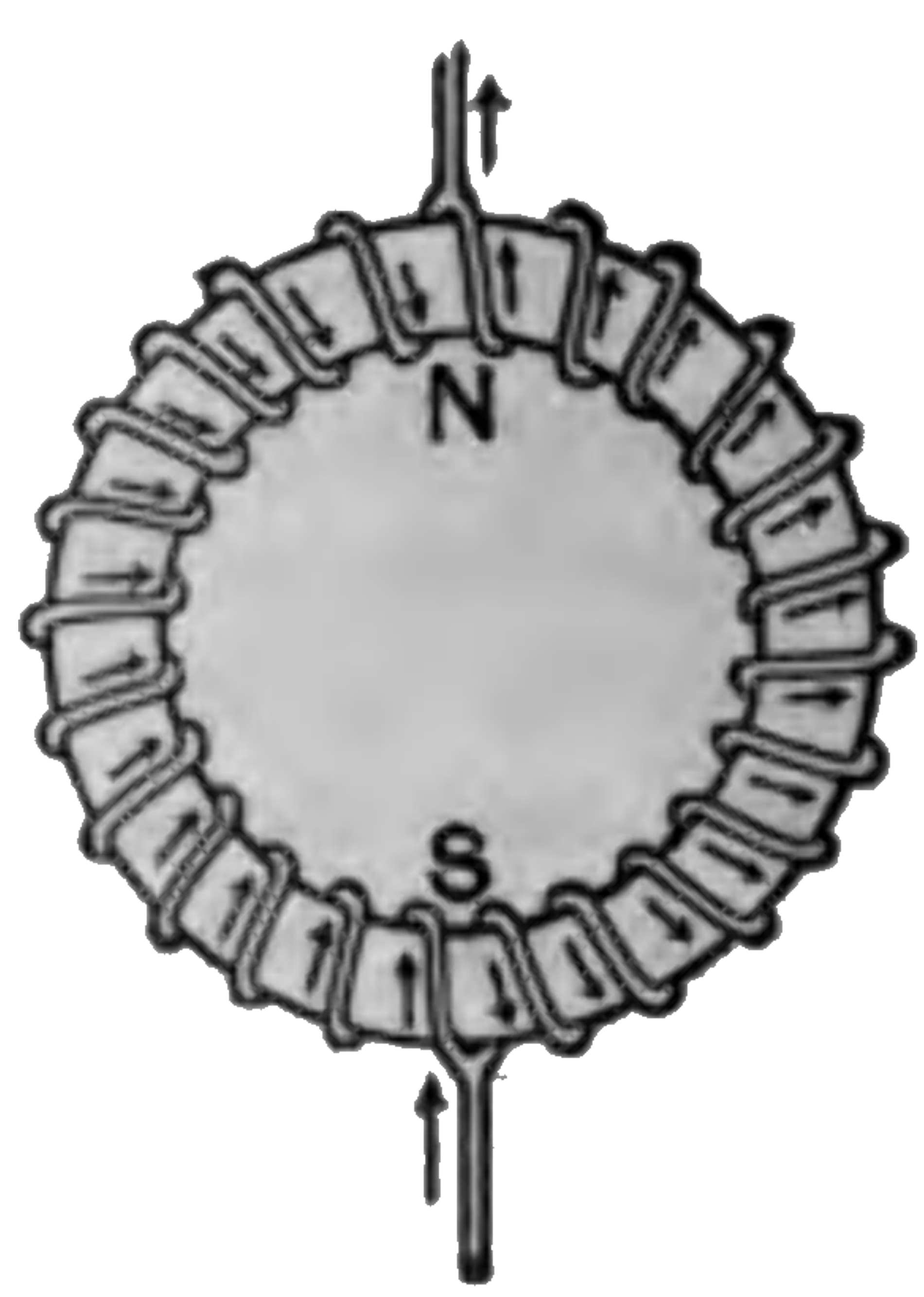


Fig. 190.

Suppose an iron core to be wound with a right-handed coil, and that a current is introduced at some point, and to flow both ways, it will produce oppositely-directed magnetizing actions in the two points, and there will be *consequent poles* (Art. 120) at the point of entrance. In Fig. 190 an iron ring with a right-handedly wound closed coil is shown. There will be a double S pole at the point where the current enters, and a double N pole where it leaves the windings.

383. Construction of Electromagnets. — The most useful form of electromagnet is that in which the iron core is bent into the form of a horse-shoe, so that both poles may be applied to one iron armature. In this

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384. Lifting-power of Electromagnets.—The tractive force of an electromagnet depends not only on its magnetic strength, but also upon its form, and on the



Fig. 192.

shape of its poles, and on the form of the soft iron armature which it attracts. It should be so arranged that as many lines of force as possible should run through the armature, and the armature itself should contain a sufficient mass of iron. Joule designed a powerful electromagnet, capable of supporting over a ton. The maximum attraction he could produce between an electromagnet and its armature was 200 lbs. per square inch, or about 13,800,000 dynes per square centimetre. Bidwell has found the attraction to go up to 226·3 lbs. per square

inch when the wrought iron core was saturated up to 19,820 magnetic lines to the square centimetre. The law of traction is that the pull per square centimetre is proportional to the square of the number of lines per square centimetre: or in symbols

$$P = \frac{B^2 A}{8\pi},$$

where P is the pull in dynes, and A the area in square centims. In the following table are given the values of the tractive force for different stages of magnetization.

B lines per sq. cm.	Dynes per sq. centim.	Grammes per sq. centim.	Pounds per sq. inch.
1,000	39,790	40·56	·577
2,000	159,200	162·3	2·308
3,000	358,100	365·1	5·190
4,000	636,600	648·9	9·228
5,000	994,700	1,014	14·39
6,000	1,432,000	1,460	20·75
7,000	1,950,000	1,987	28·26
8,000	2,547,000	2,596	36·95
9,000	3,223,000	3,286	46·72
10,000	3,979,000	4,056	57·68
12,000	5,730,000	5,841	83·07
14,000	7,800,000	7,950	113·1
16,000	10,170,000	10,390	147·7
18,000	12,890,000	13,140	186·8
20,000	15,920,000	16,230	230·8

It will be noted that doubling **B** makes the pull four times as great. One curious consequence of this law is that to enlarge its poles weakens the pull of an electromagnet or magnet. In some cases—bar magnets for example—their tractive power is increased by filing down or rounding the poles so as to concentrate **B**.

385. Solenoid. — Without any central core of iron or steel a spiral coil of wire traversed by a current acts as an electromagnet (though not so powerfully as when an iron core is placed in it). Such a coil is sometimes termed a solenoid. A solenoid has two poles and a neutral equatorial region. Ampère found that it will attract magnets and be attracted by magnets. It will attract another solenoid; it has a magnetic field resembling generally that of a bar magnet. If so arranged that it can turn round a vertical axis, it will set itself in a North and South direction along the magnetic meridian. Fig. 193 shows a solenoid arranged with pivots, by which it can be suspended to a "table," like that shown in Fig. 198.

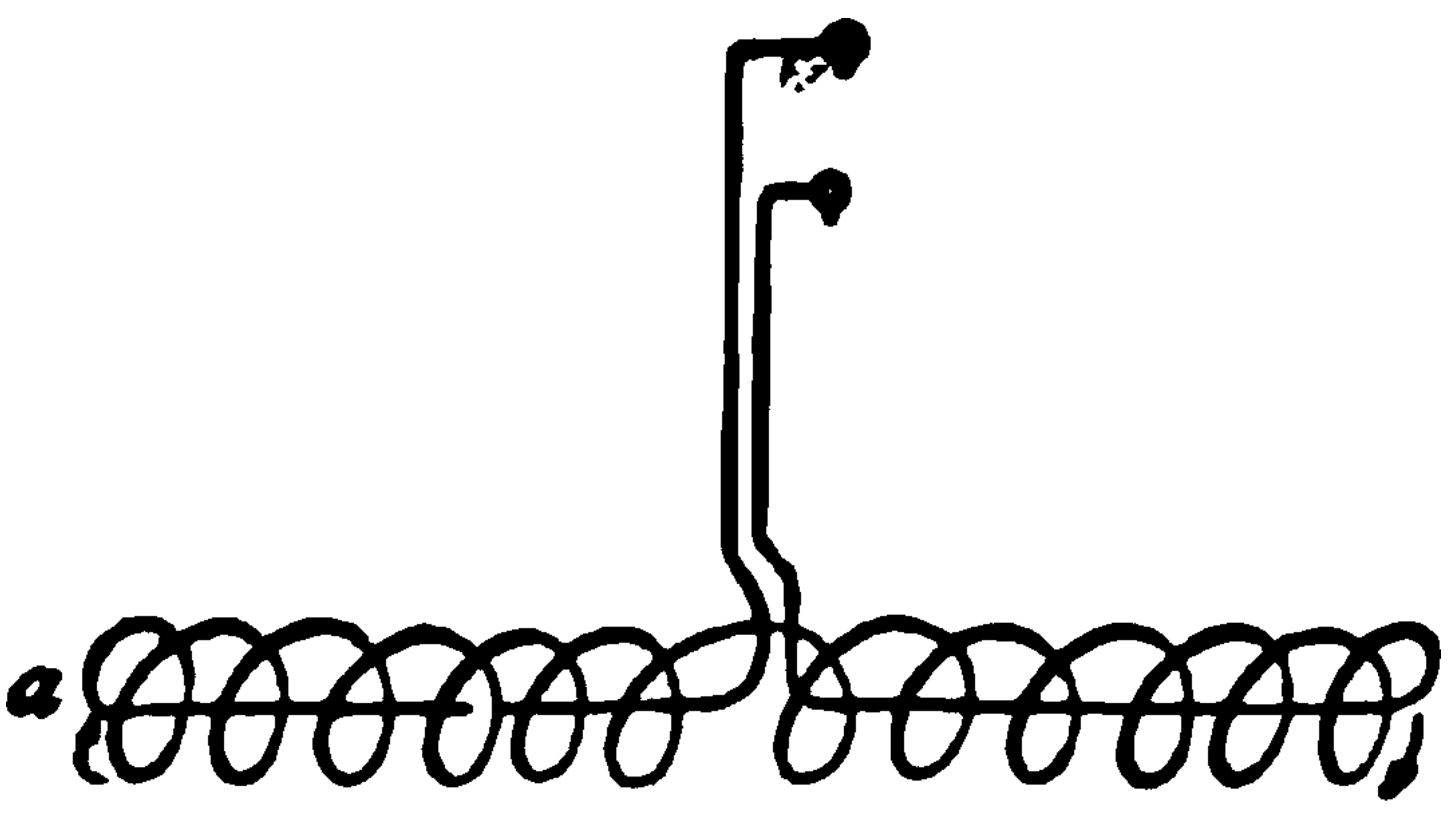


Fig. 193.

With an iron core the solenoid becomes far more powerful. The effect of the iron core is by its greater permeability to multiply the number of magnetic lines as well as to concentrate them at definite poles. The student has been told (Art. 202) that the lines of force due to a current flowing in a wire are closed curves, approximately circles (Figs. 115 and 195), round the wire. If there were no iron core many of these little circular lines of force would simply remain as small closed curves around their own wire; but, since iron has a permeability hundreds of times greater than air, wherever the wire passes near an iron core the magnetic lines alter their shape, and instead of being little circles around the separate wires, run through the iron core from end to end, and round outside from one end of the coil back to the other. A *few* of the magnetic lines do this when there is no iron; almost all of them do this when there is iron, and when

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down the coil, diminishing quickly as the core emerges. Short iron cores are only pulled while at the mouth of the coil; the maximum pull being when about half their length has entered.

386. The Winding of Electromagnets.—The exact laws governing the winding of electromagnets are somewhat complicated; but it is easy to give certain rules which are approximately true. Every electromagnet shows the same general set of facts—that with small exciting power there is little magnetism produced, with larger exciting power there is more magnetism, and that with very great exciting power the iron becomes practically saturated and will take up very little additional magnetism. It follows at once that if the electromagnet is destined to be used at the end of a long line through which only a small current (perhaps only $\frac{1}{100}$ ampere) will flow, the requisite number of ampere-turns to excite the magnetism will not be attained unless many turns of wire are used; and as the current is small a fine wire may be used.

It may be noted that when electromagnets are wound with many turns of fine wire, these coils will add to the electric resistance of the circuit, and will tend to diminish the current. Herein lies a difference in construction of telegraphic and other instruments; for while electromagnets with "long coils," consisting of many turns of fine wire, must be used on long circuits where there is great line resistance, such an instrument would be of no service in a laboratory circuit of very small resistance, for the resistance of a long thin coil would be disproportionately great: here a short coil of few turns of stout wire would be appropriate (see Art. 192).

It is the nature of the *line*, according to whether it is of high resistance or low, which governs the questions how the coil shall be wound and how the battery shall be grouped.

Similar electromagnets of different sizes must have

ampere-turns proportional to their linear dimensions if they are to be raised to equal degree of saturation.

As the magnetism of the magnet depends on the number of ampere-turns, it should make no matter whether the coils are bigger than the core or whether they enwrap it quite closely. If there were no magnetic leakage this would be true in one sense; but for an equal number of turns large coils cost more and offer higher resistance. Hence the coils are wound as closely to the iron core as is consistent with good insulation. Also the iron is chosen as thick as possible, as permeable as possible, and forming as compact a magnetic circuit as possible, so that the magnetic resistance may be reduced to its utmost, giving the greatest amount of magnetism for the number of ampere-turns of excitation. This is why horse-shoe-shaped electromagnets are more powerful than straight electromagnets of equal weight; and why also a horse-shoe electromagnet will only lift about a quarter as much load if one pole only is used instead of both.

As the coils of electromagnets grow hot with the current, sufficient cooling surface must be allowed, or they may char their insulation. Each square centimetre of surface warmed 1° C. above the surrounding air can get rid of about 0·0029 *watt*. If 50° above the surrounding air be taken as the safe limit of rise of temperature, and the electromagnet has resistance r and surface s sq. cms., the highest permissible current will be $0{\cdot}38\ \sqrt{s/r}$ amperes.

387. Polarized Mechanism. — An electromagnet moves its armature one way, no matter which way the current flows. Reversing the current makes no difference. There are, however, two ways of making a mechanism that will cause an armature to move in either sense at will. (*a*) The armature's movement is controlled by an adjusted spring so as to be in an intermediate position when a weak current is flowing. Then sending a stronger current will move the armature one way, and weakening

or stopping the current will make it move the other way. (*b*) A *polarized* armature or tongue (*i.e.* one that is independently magnetized) is placed *between the poles* of the electromagnet instead of opposite them. The direction in which it tends to move will be reversed by reversing the current in the circuit of the electromagnet.

388. Growth of Magnetism. — It requires time to magnetize an iron core. This is mainly due to the fact that a current, when first switched on, does not instantly attain its full strength, being retarded by the self-induced counter-electromotive-force (Art. 458); it is partly due to the presence of transient reverse eddy-currents (Art. 457) induced in the iron itself. Faraday's large electromagnet at the Royal Institution takes about two seconds to attain its maximum strength. The electromagnets of large dynamo machines often take ten minutes or more to rise to their working stage of magnetization.

When electromagnets are used with rapidly alternating currents (Art. 470) there are various different phenomena, for which the student is referred to Art. 477.

Lesson XXXII. — *Electrodynamics*

389. Electrodynamics. — In 1821, almost immediately after Oersted's discovery of the action of a current on a magnet, Ampère discovered that a current acts upon another current, apparently attracting it * or repelling it according to certain definite laws. These actions he investigated by experiment, and from the experiments he built up a theory of the force exerted by one current on another. That part of the science which is concerned with the force which one current exerts upon another he termed **Electrodynamics**. It is now known that these

* It would be more correct to speak of the force as acting on *conductors carrying currents*, than as acting on the currents themselves.

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by the general law of electromagnetic systems (Art. 379), because shortening will reduce the reluctance of the magnetic circuit and increase the flux.

(ii.) *Two portions of circuits crossing one another obliquely attract one another if both the currents run either towards or from the point of crossing, and repel one another if one runs to and the other from that point.*

Fig. 196 gives three cases of attraction and two of repulsion that occur in these laws.

(iii.) *When an element of a circuit exerts a force on another element of a circuit, that force always tends to urge*

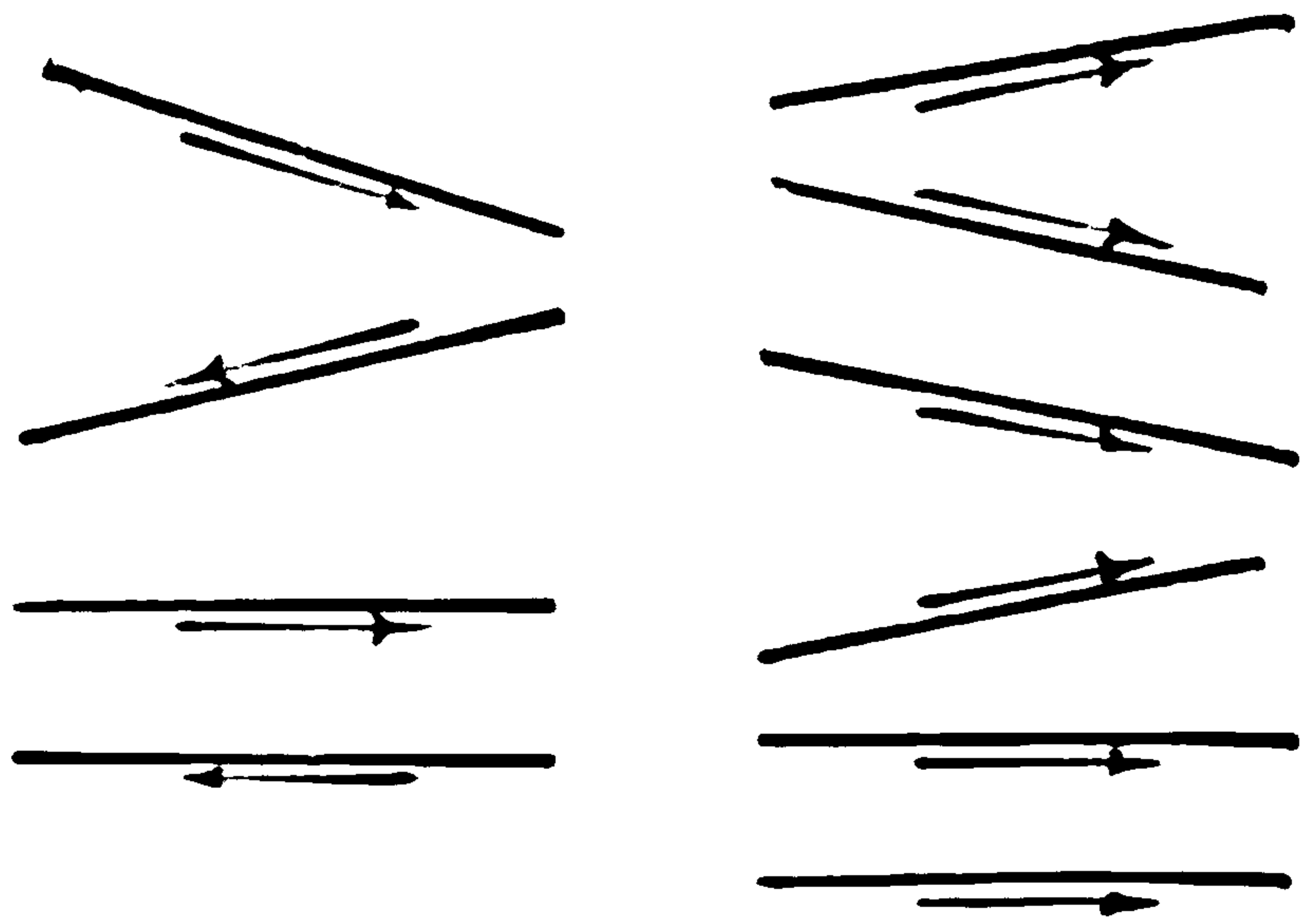


Fig. 196.

the latter in a direction at right angles to its own direction. Thus, in the case of two parallel circuits, the force of attraction or repulsion acts at right angles to the currents themselves.

An example of laws ii. and iii. is afforded by the case shown in Fig. 197. Here two currents *ab* and *cd* are movable round O as a centre. There will be an apparent *repulsion* between *a* and *d* and between *c* and *b*, while in the other quadrants there will be an apparent *attraction*, *a* attracting *c*, and *b* attracting *d*.

The foregoing laws may be summed up in one, by saying that two portions of circuits, however situated, set up stresses in the surrounding medium tending to set them so that their currents flow as nearly in the same path as possible.

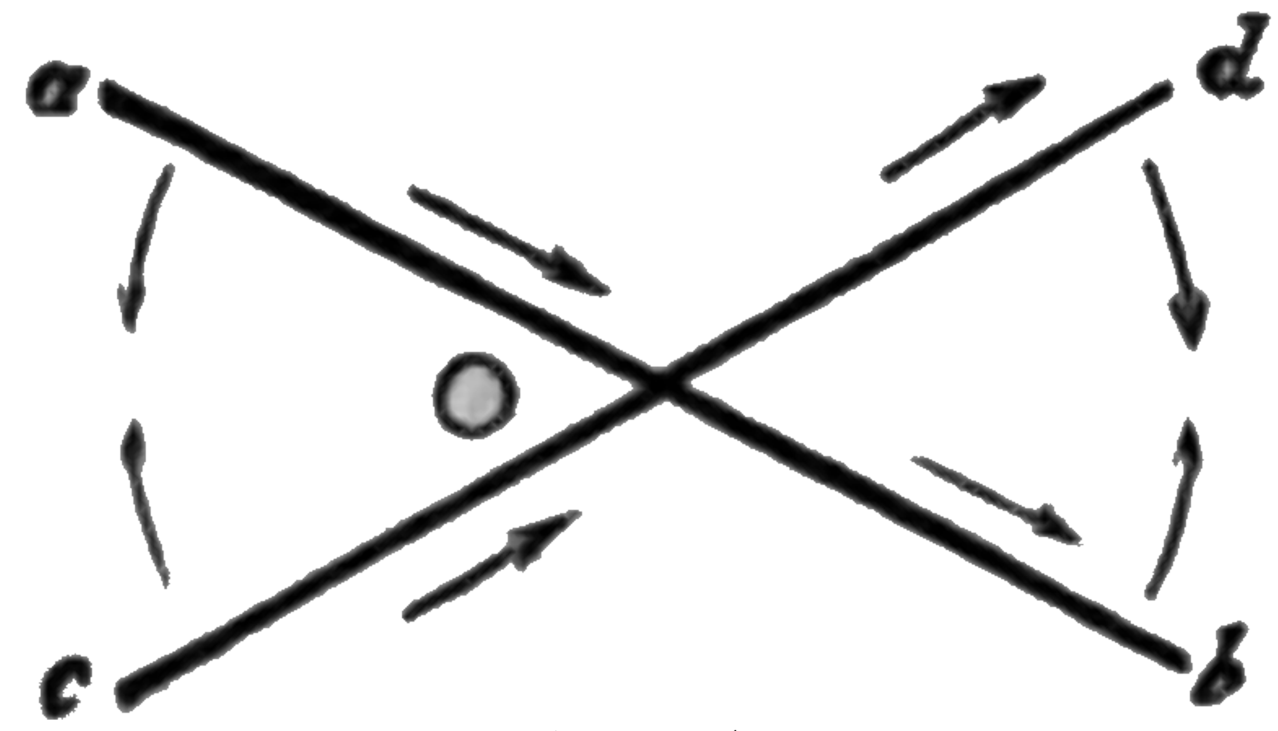


Fig. 197.

(iv.) *The force exerted between two parallel portions of circuits is proportional to the product of the strengths of the two currents, to the length of the portions, and inversely proportional to the simple distance between them.*

391. Ampère's Table.—In order to observe these attractions and repulsions, Ampère devised the piece of

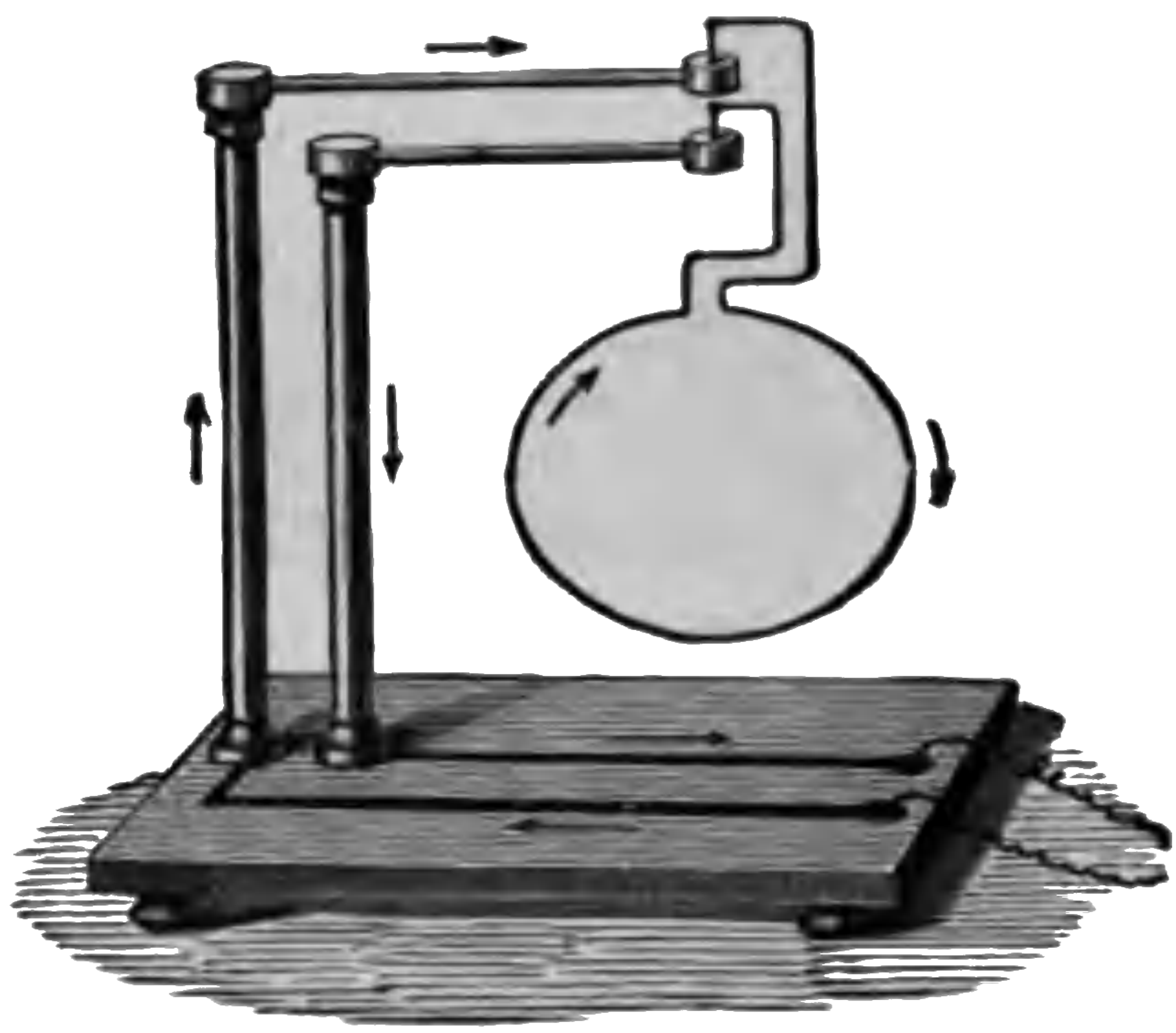


Fig. 198.

apparatus known as *Ampère's Table*, shown in Fig. 198, consisting of a double supporting stand, upon which wires, shaped in different ways, can be so hung as to be capable of rotation. The ends of the suspended wires

dip into two mercury cups, so as to ensure good contact, while allowing freedom to move.

By the aid of this piece of apparatus Ampère further demonstrated the following points:—

(*a*) A circuit doubled back upon itself, so that the current flows back along a path close to itself, exerts no force upon external points.

(*b*) A circuit bent into zig-zags or sinuosities produces the same magnetic effects on a neighbouring piece of circuit as if it were straight.

(*c*) There is in no case any force tending to move a conductor in the direction of its own length.

(*d*) The force between two conductors of any form is the same, whatever the linear size of the system, provided the distances be increased in the same proportion, and that the currents remain the same in strength.

The particular case, given in Fig. 199, will show the value of these experiments. Let AB and CD represent two wires carrying currents, lying neither parallel nor in the same plane. It follows from (*b*) that if we replace the portion PQ by the crooked

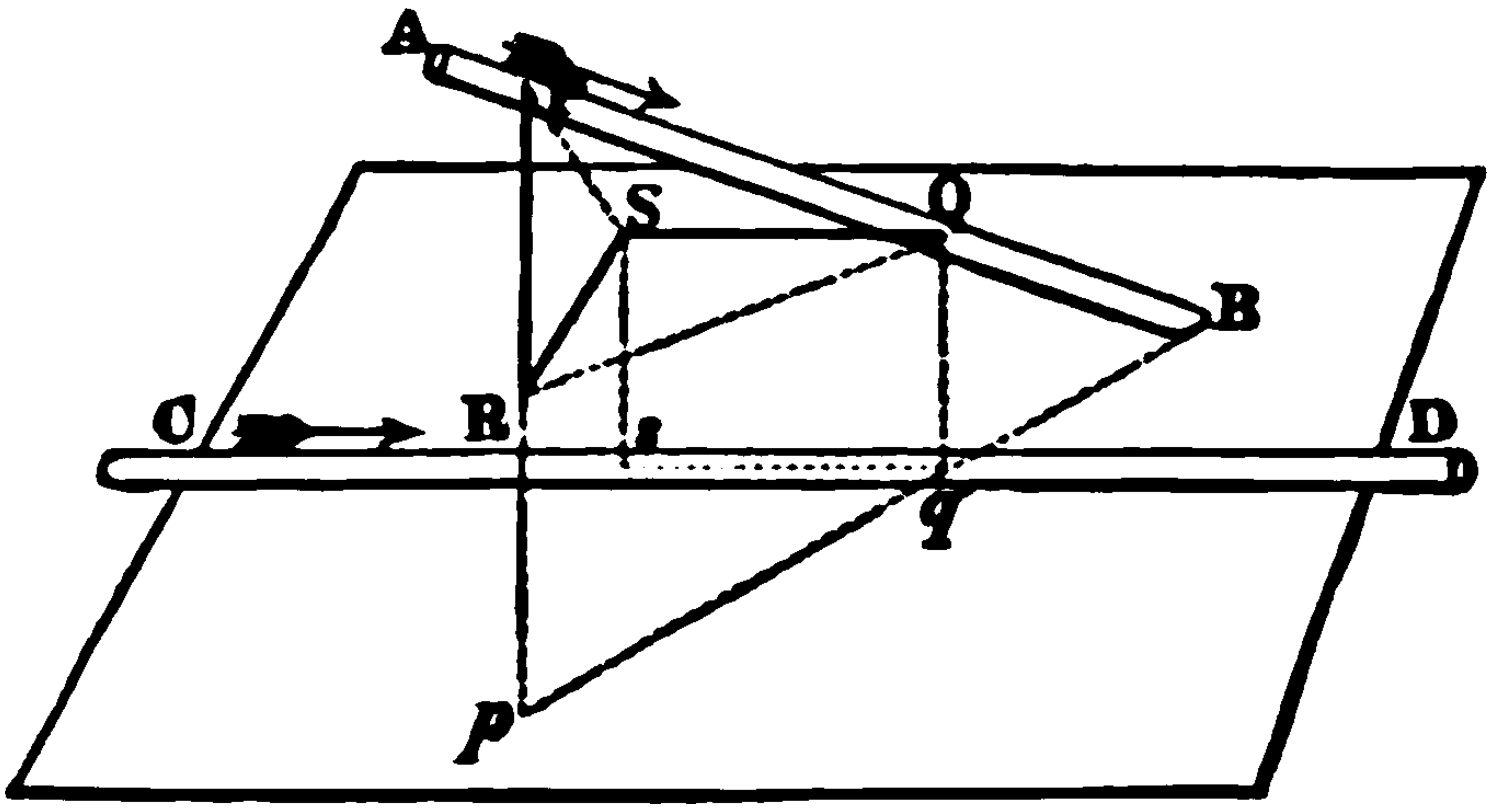


Fig. 199.

wire PRSQ, the force will remain the same. The portion PR is drawn vertically downwards, and as it can, by (*c*), experience no force in the direction of its length, this portion will neither be attracted nor repelled by CD. In the portion RS the current runs at right angles to CD, and this portion is neither attracted nor repelled by CD. In the portion SQ the current runs parallel to CD, and in the same direction, and will therefore be attracted downwards. On the whole therefore, PQ will be urged towards

metallic bridge formed of a bent wire, of the form shown in Fig. 200, or consisting of a glass tube filled siphonwise with mercury. When a current is sent through the

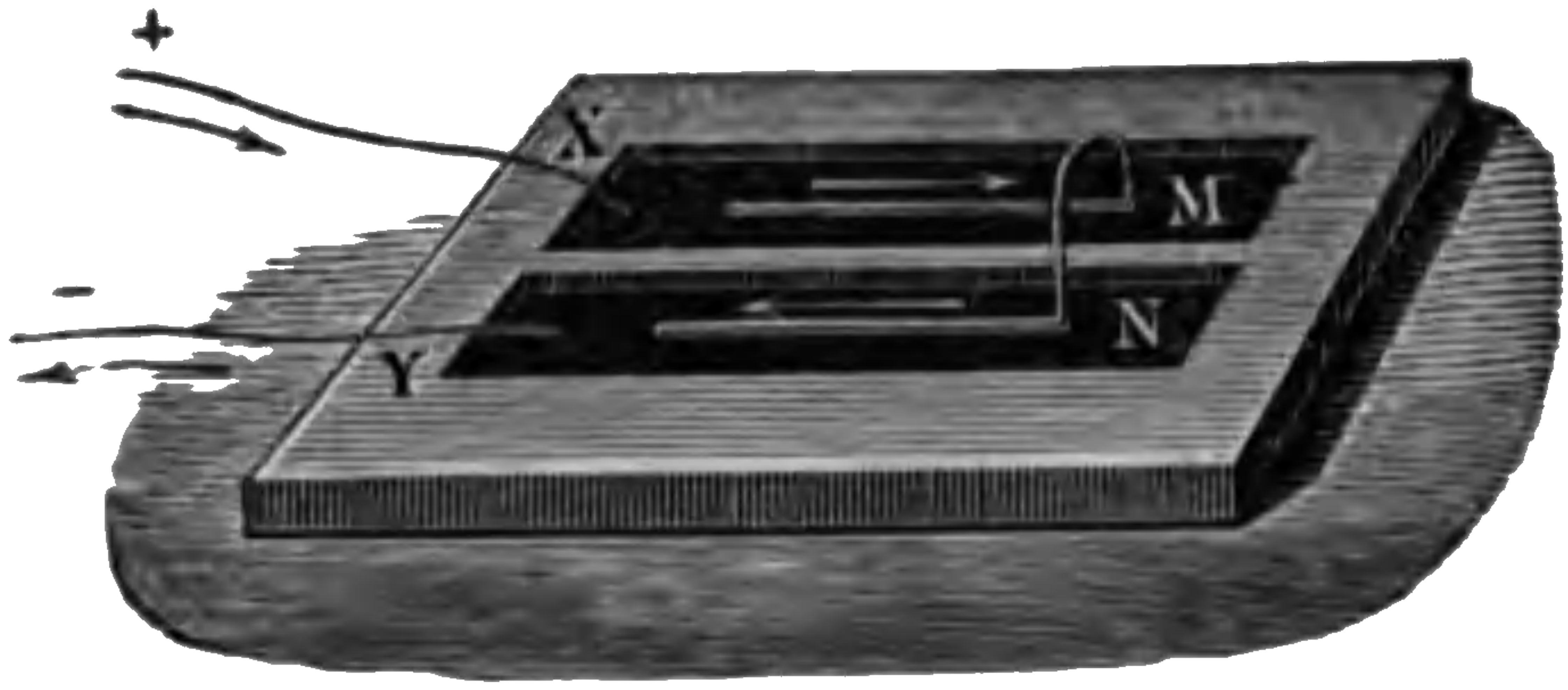


Fig. 200.

floating conductor from X over MN, and out at Y, the floating bridge is observed to move so as to increase the area enclosed by the circuit. But the force would be diminished indefinitely if the two parallel parts could be made to lie quite close to one another.

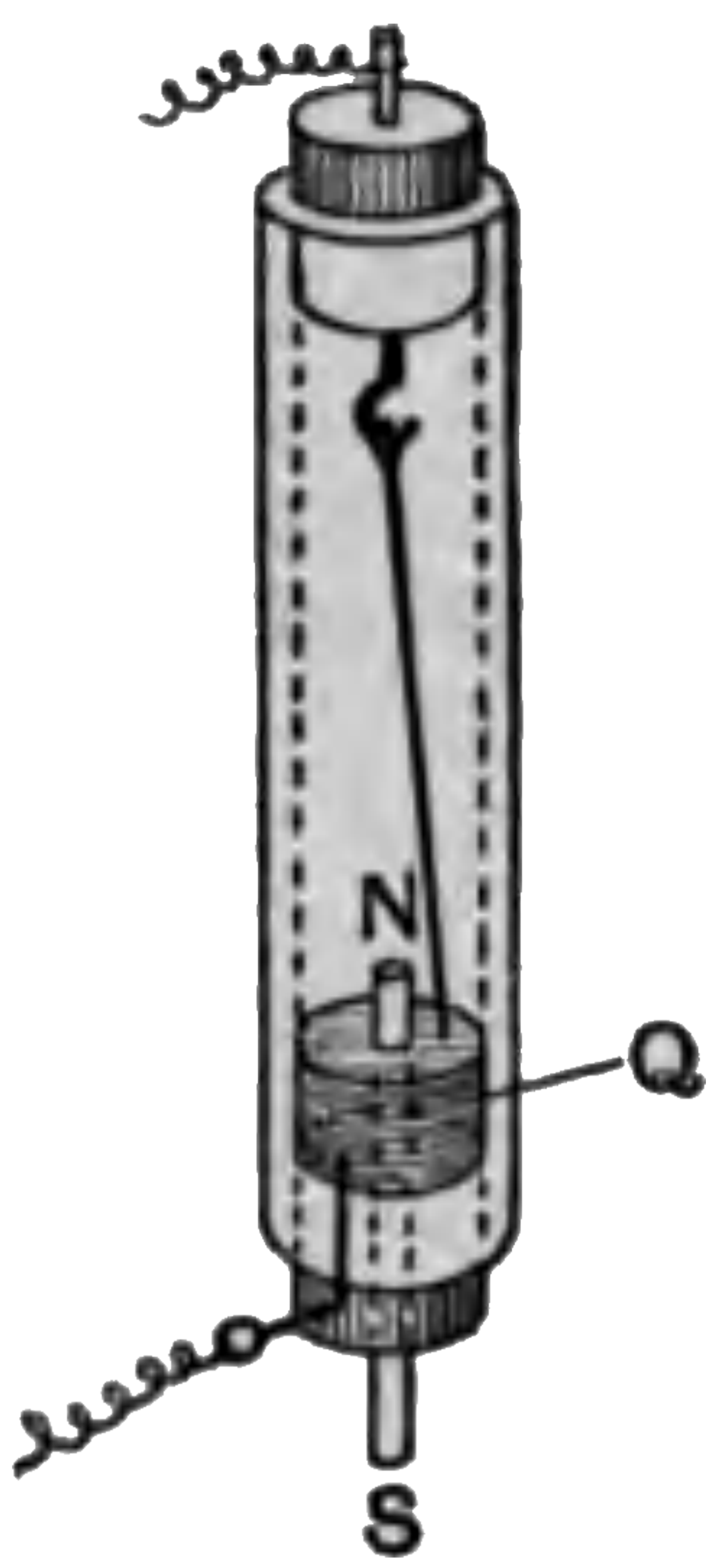


Fig. 201.

393. Electromagnetic Rotations. — Continuous rotation can be produced between a magnet and a circuit, or between two parts of one circuit, provided that one part of the circuit can move while another part remains fixed, or that the current in one part can be reversed. The latter device is adopted in the construction of *electric motors* (Art. 448). The former alternative is applied in some historic apparatus for showing rotations, a sliding-contact being made between one part of the circuit and another. Several different forms of rotation-apparatus were devised by Faraday and by Ampère. One of Faraday's is shown in Fig. 201, in which a wire carrying a current is jointed at the top and dips into a cup of

mercury surrounding the pole of a magnet. On switching on the current the wire at once begins to walk round the pole with a motion that continues until the current is switched off.

A pole of a magnet can also be made to rotate round a current; and if a vertical magnet be pivoted so as to turn around its own axis it will rotate when a current is led into its middle region and out at either end. If the current is led in at one end and out at the other there will be no rotation, since the two poles would thus be urged to rotate in opposite ways. Liquid conductors too can exhibit electromagnetic rotations. Let a cylindrical metallic vessel connected to one pole of a battery be filled with mercury or dilute acid, and let a wire from the other pole dip into its middle, so that a current may flow radially from the centre to the circumference, or *vice versa*; then, if this be placed upon the pole of a powerful magnet, or if a magnet be held vertically over it, the liquid may be seen to rotate.

394. Electrodynamometer.—Weber devised an instrument known as an *electrodynamometer* for measuring the strength of currents by means of the electrodynamic action of one part of the circuit upon another part. It is a sort of galvanometer, in which, instead of a needle, there is a small coil suspended. One form of this instrument, in which both the large outer and small inner coils consist of two parallel coils of many turns, is shown in Fig. 202. The inner coil CD is suspended with its axis at right angles to that of the outer coils AA, BB, and is supported *bifilarly* (see Art. 130) by two fine metal wires. If one current flows round *both* coils *in either direction* the inner bobbin tends to turn and set its coils parallel to the outer coils; the sine of the angle through which the suspending wires are twisted being proportional to the square of the strength of the current.

If G be the "principal constant" (Art. 213) of the large coils, and *g* the "moment" of the small coils (Art. 346) when carrying

unit current, and C_1C_2 the currents in them, the torque (or turning moment) will be

$$=G_g C_1 C_2/100.$$

The chief advantage of this instrument over a galvanometer is, that it may be used for alternating currents; a

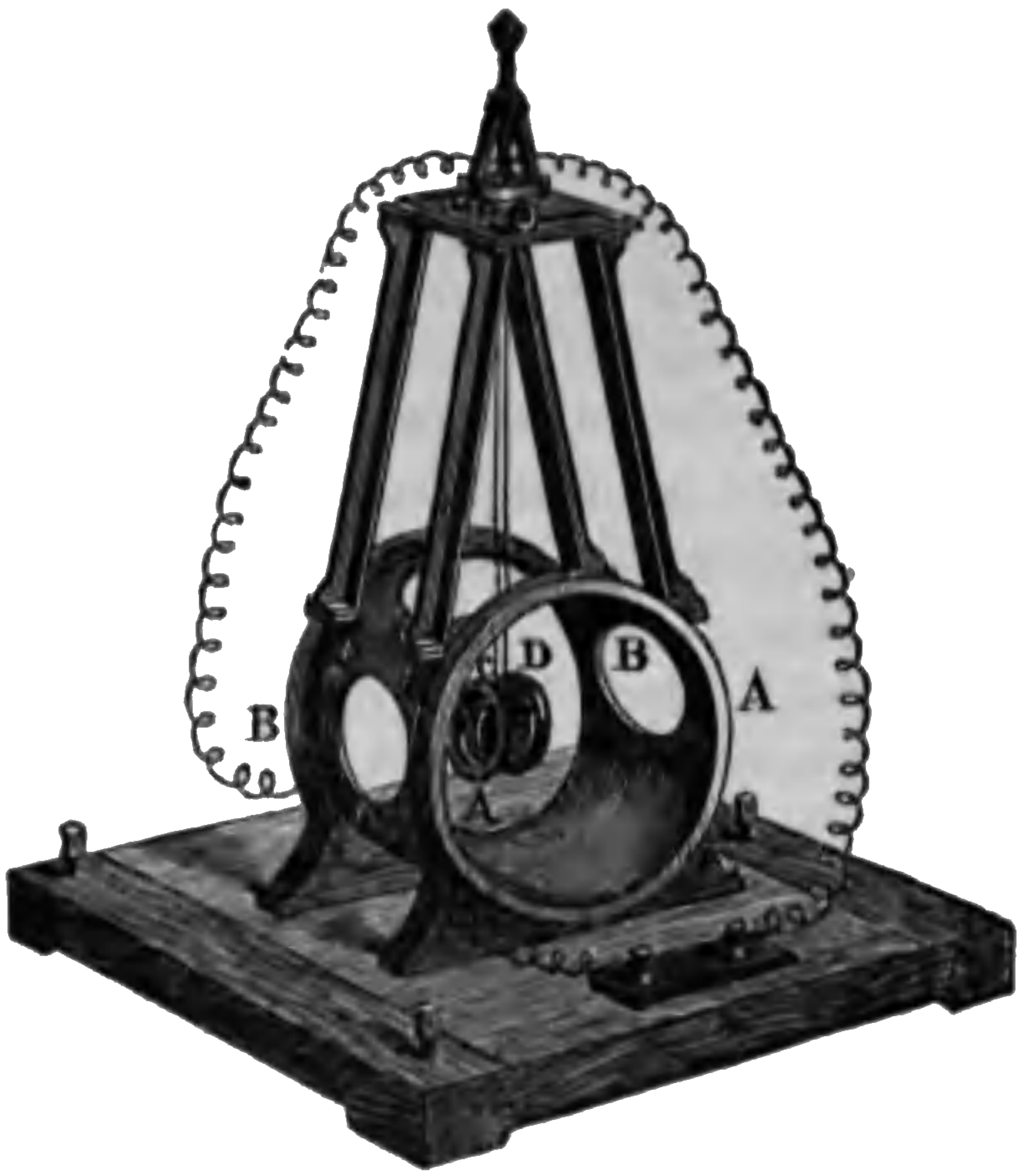


Fig. 202.

current in one direction being followed by a reverse current, perhaps thousands of times in a minute. Such currents hardly affect a galvanometer needle at all; the needle simply quivers in its place without turning.

395. Siemens's Electrodynamometer. — In Siemens's dynamometer (Fig. 203), much used for measurement of strong currents, whether of the continuous or the alternating kind, one coil is fixed permanently, whilst the other coil, of one or two turns, dipping with its ends in mercury cups, is hung at right angles, and controlled by a spiral spring below a torsion-head.

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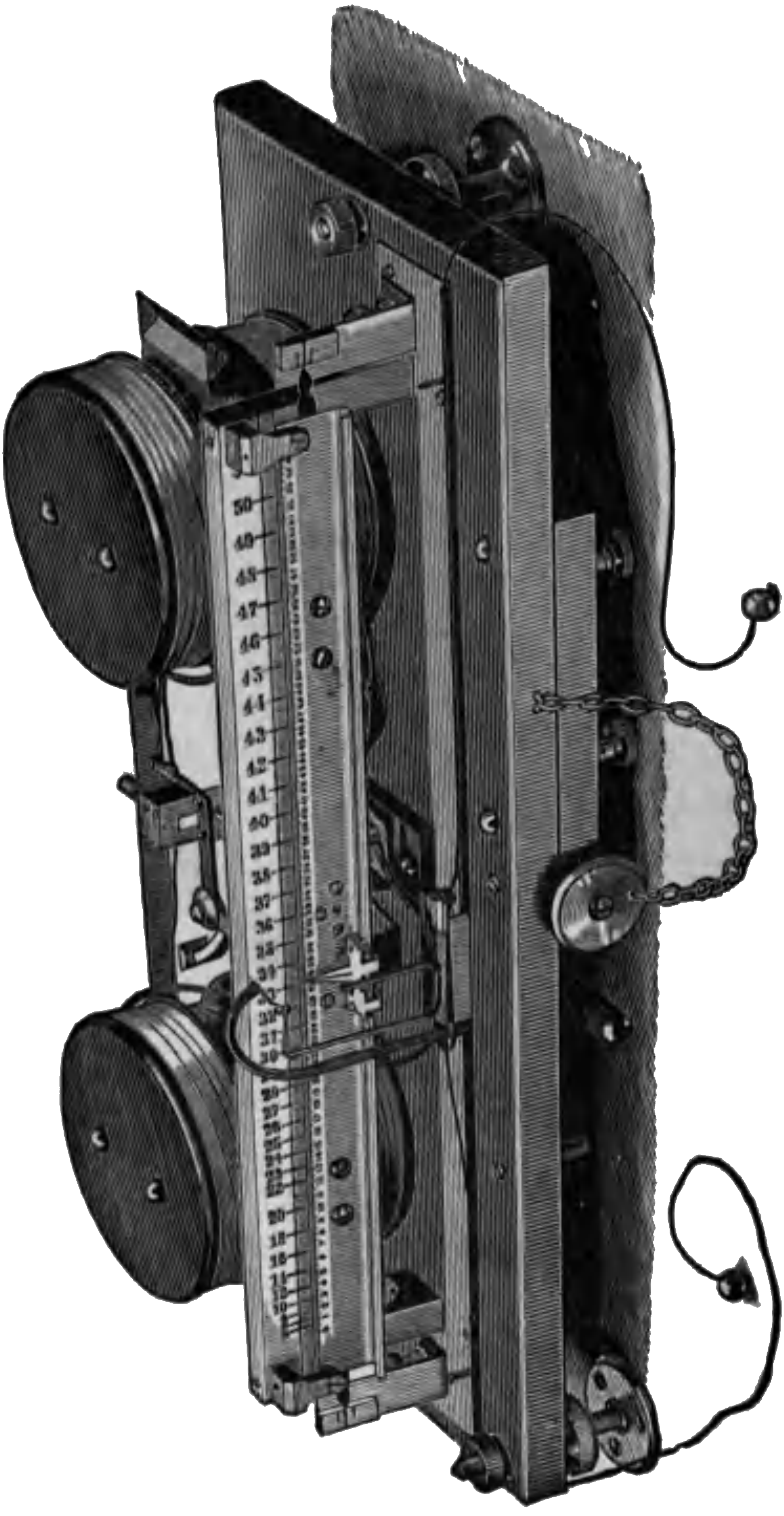


Fig. 205.

force is proportional to the product of the current in the fixed and movable coils as in all electrodynamometers.

Lord Kelvin has designed a whole range* of these instruments: — a *centi-ampere* balance reading from 0·01 to 1 ampere; a *deci-ampere* balance reading from 0·1 to 10; a *deka-ampere* balance reading from 1 to 100; a *hekto-ampere* balance reading from 6 to 600; and a *kilo-ampere* balance reading up to 2500 amperes. The *centi-ampere* balance is shown in Fig. 205, in which the sliding weight is carried on the base of the pointer (shown white), and when at the zero of the scale just balances the weight in the V-shaped pan. Any current passing through the coils causes the beam to tilt and the pointer is moved (by means of a self-releasing slider attached to cords) until it is again horizontal (as shown by the black pointer at either end). With a certain pair of weights the fixed scale gives the current in decimal parts of an ampere; but by the use of other weights a wider range is obtained.

The "ampere-standard" instrument, and the "volt-standard" instruments of the Board of Trade, kept at Whitehall as legal standards for Great Britain, embodying the international units, are current balances of special construction, designed by Major Cardew.

397. Electromagnetic Actions of Convexion Currents. —According to Faraday a stream of particles charged with electricity acts magnetically like a true conduction current. This was first proved in 1876 by Rowland, who found a charged disk rotated rapidly to act upon a magnet as a feeble circular current would do. Convexion currents, consisting of streams of electrified particles, are also acted upon by magnets. The convective discharges in vacuum-tubes (Art. 320) can be drawn aside by a magnet, or caused to rotate around a magnet-pole. The brush discharge (Art. 319) when taking place in a strong magnetic field is twisted. The electric arc (Art. 448) also behaves like a flexible conductor, and can be attracted or repelled laterally by a magnet. Two stationary positively electrified particles repel one another, but two

* For a fuller account of these Current Balances, and of the Wattmeters on the same principle, see Gray's *Absolute Measurements in Electricity and Magnetism*, from which Fig. 205 is taken.

parallel currents attract one another (Art. 390), and if electrified particles flowing along act like currents, there should be an (electromagnetic) attraction between two electrified particles moving along side by side through space. According to Maxwell's theory (Art. 518) the electrostatic repulsion will be just equal to the electromagnetic attraction when the particles move with a velocity equal to the velocity of light.

Hall discovered in 1879 that when a powerful magnet is made to act upon a current flowing along in a strip of very thin metal, the equipotential lines are no longer at right angles to the lines of flow of the current in the strip. This action appears to be connected with the magnetic rotation of polarized light (Art. 526), the coefficient of this transverse thrust of the magnetic field on the current being feebly + in gold, strongly + in bismuth, and − in iron, and immensely strong negatively in tellurium. It was shown by the author, and about the same time by Righi, that those metals which manifest the Hall cffeet undergo a change in their electric resistance when placed in the magnetic field. The resistance of bismuth increases so greatly that it affords a way of measuring the strength of magnetic fields.

398. Ampère's Theory of Magnetism.—Ampère, finding that solenoids (such as Fig. 193) act precisely as magnets, conceived that all magnets are simply collections of currents, or that around every individual molecule of a magnet an electric current is ceaselessly circulating. We know that such currents could not flow perpetually if there were any resistance to them, and we know that there is resistance when electricity flows from one molecule to another. As we know nothing about the interior of molecules themselves, we cannot assert that Ampère's supposition is impossible. Since a whirlpool of electricity acts like a magnet, there seems indeed reason to think that magnets may be merely made up of rotating portions of electrified matter.

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other parts of the circuit. For example, the current may flow from the zinc plate of the first cell through the liquid to the carbon plate, then through a connecting wire or screw to the next cell, through its liquid, through the connecting screws and liquids of the rest of the cells, then through a wire to a galvanometer, then through the coils of the galvanometer, then perhaps through an electrolytic cell, and finally through a return wire to the zinc pole of the battery. In this case there are a number of separate electromotive-forces all tending to produce a flow, and a number of different resistances, each obstructing the flow and adding to the total resistance. If in such a case we knew the separate values of all the different electromotive-forces and all the different resistances that are in series we could calculate what the current would be, for it would have the value—

$$C = \frac{e' + e'' + e''' + e^{iv} + \cdot\cdot\cdot\cdot\cdot\cdot\cdot}{r' + r'' + r''' + r^{iv} + \cdot\cdot\cdot\cdot\cdot\cdot\cdot}$$

$$C = \frac{\text{Total electromotive-force}}{\text{Total resistance}}.$$

> *Example.*—Let there be 5 cells in series each having $e =$ 1·4 volts, and each an internal $r = 0{\cdot}4$ ohm; and let the external part of circuit have resistance 3 ohms. Total E = 7 volts; total R = 5 ohms. Current C will be $1\frac{2}{5}$ amperes.

If any one of the cells were set wrong way round its electromotive-force would oppose that of the other cells; an opposing electromotive-force must therefore be subtracted, or reckoned as negative in the algebraic sum. The "polarization" (Arts. 175 and 487) which occurs in battery cells and in electrolytic cells after working for some time is an opposing electromotive-force, and diminishes the total of the electromotive-forces in the circuit. So, also, the induced back E.M.F. which is set up when a current from a battery drives an electric motor (Art. 444) reduces the strength of the working

current; in such case, if E is the electromotive-force of the battery, e the opposing electromotive-force, and R the total resistance, we shall have

$$C = \frac{E - e}{R}.$$

Example.—Suppose the battery to generate current at 25 volts, and the motor to generate a back electromotive-force of 20 volts, and the total resistance to be 2½ ohms, there will be a current of 2 amperes.

But we may apply Ohm's law to a *part* of a circuit. If e represents the difference of potential between two ends of a conductor of resistance r, the current C in it must be $= e/r$. Or, to put it the other way round, the electromotive-force needed to drive C amperes through a resistance of r ohms will be $e = r$C volts.

Consider the case of a circuit of which the resistance is made up of two parts, an external resistance R consisting of wires, lamps, etc., and of a smaller resistance r internal to the battery or dynamo (viz. the resistance of the liquids in the cells, or of the wire of the armature). Then if E is the whole electromotive-force we shall have as current

$$C = \frac{E}{R + r},$$

or $$C(R + r) = E;$$

or again $$CR + Cr = E.$$

This means in words that the total volts may be considered as being employed partly in driving the current through the external resistance R, partly in driving the current through the internal resistance r. This latter part of the electromotive-force is called the *lost volts;* the remainder being the useful or externally available volts, that would be measurable by a voltmeter (Art. 220) set across the terminals. If we call the available volts V we may write V = CR, whence

$$V = E - Cr;$$

or in words: the volts as measured at the terminals of a cell or dynamo are less than the whole E.M.F. generated therein; being equal to the whole E.M.F. less the lost volts. The lost volts being proportional to internal resistance it is obviously best to keep all internal resistances as low as possible. Only when the cell is giving no current are the external volts V equal to the whole E.M.F.; for when $C = o$, Cr is also $= o$.

> *Example.*—A dynamo is designed to generate its currents with an electromotive-force of 105 volts. The internal resistance of its armature is $\frac{1}{30}$ ohm. When it is giving out current of 120 amperes, the lost volts will be $120 \times \frac{1}{30} = 4$ volts. Consequently the volts available in the external circuit will be only 101.

Since $C = \frac{E}{R+r} = \frac{V}{R}$ it follows also that $V = E \frac{R}{R+r}$.

400. Resistance.—Resistance is the name given to that property of materials by virtue of which they obstruct the steady flow of electricity through them, and fritter down into heat the energy of the current. It is found that the resistance of a metal wire, if kept at an unvarying temperature, is the same whether a large current or a small current be flowing through it. For example, if a wire has a resistance such that when a difference of potential of 10 volts is applied to its ends a current of 2 amperes flows through it (its resistance being 5 ohms), it will be found that if 1 volt is applied the current will be 0.2 amperes, the ratio between volts and amperes being 5 as before.

The unit of resistance, or *ohm*, is a standard chosen in order that the resistances of other conductors may be expressed in definite numbers. The definition of it is given in Art. 354. It is convenient to remember that 100 yards of ordinary iron telegraph-wire has roughly a resistance about 1 ohm.

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resistance by squeezing them together into better contact.

401. Laws of Resistance.—The following are the laws of the resistance of conductors:—

(i.) *The resistance of a conducting wire is proportional to its length.* If the resistance of a mile of iron telegraph wire be 17 ohms, that of 50 miles will be $50 \times 17 = 850$ ohms.

(ii.) *The resistance of a conducting wire is inversely proportional to the area of its cross-section*, and therefore in the usual round wires *is inversely proportional to the square of its diameter*. Ordinary telegraph wire is about $\frac{1}{8}$ of an inch thick; a wire twice as thick would conduct four times as well, having four times the area of cross-section; hence an equal length of it would have only $\frac{1}{4}$ the resistance.

(iii.) *The resistance of a conducting wire of given length and thickness depends upon* the material of which it is made—that is to say, upon *the* specific resistance *of the material.*

If the length of a wire be l centimetres, and its area of section A square centimetres, and the specific resistance of the material be ρ, then its resistance R will be

$$R = l\rho / A.$$

Example.—Find the resistance of a platinoid wire of section 0·004 sq. cm., and 200 cm. long; $\rho = 32·5 \times 10^{-6}$. R = 1·625 *ohms.*

402. Conductance and Resistance.—The term *conductance* is used as the inverse of resistance; a conductor whose resistance is r ohms is said to have a conductance of $1/r$ "*mhos.*" When a number of conductors are *in parallel* with one another their united conductance is the sum of their separate conductances.

The conductance of a prism of which the length is

1 cm. and its area of section is 1 sq. cm., is called its *conductivity* or *specific conductance.*

The resistance of a prism of length 1 cm. and section 1 sq. cm. is sometimes called its *resistivity* or *specific resistance.*

403. Specific Resistance.—The specific resistance of a substance is most conveniently stated as the resistance (in millionths of an ohm) of a centimetre cube of the substance. The Table on p. 404 also gives the relative conductance when that of copper is taken as 100:—

Aluminium is a better conductor than silver, weight for weight.

It is found that those substances that possess a high conducting power for heat are also the best conductors of electricity, but the ratio of these conductivities is not constant; it varies as the absolute temperature.

Liquids fall under three heads: (1) molten metals and alloys, which conduct simply as metals; (2) fused salts and solutions of salts and acids, which conduct only *by electrolysis* (Art. 487); (3) insulators, such as the oils, turpentine, etc., and bromine. Liquid electrolytes are worse conductors than metals; gases, including steam, are perfect non-conductors, except when so rarefied as to admit of discharge by convexion through them (Art. 320).

404. Effects of Heat on Resistance.—Changes of temperature affect temporarily the conducting power of metals. Nearly all the pure metals increase their resistance about 0·4 per cent for a rise of 1° C. in temperature, or about 40 per cent when warmed 100°. When cooled in liquid oxygen the resistance was found by Wroblewski to fall greatly. A copper wire which at 0° had a resistance of 17·5 ohms fell to 1·65 ohms at − 201° C. Dewar and Fleming find all pure metals to lower their resistance as though at − 274° C. (absolute zero of temperature) they would become perfect conductors. The resistance of carbon, on the other hand, diminishes on heating. The filament of a glow-lamp,

TABLE OF SPECIFIC RESISTANCE.

Substance.	Specific Resistance (microhms of 1 cm. cube).	Resistance (ohms) of metre length 1 sq. mm. Section.	Relative Conductance.
Metals at 0° C.			
Copper (annealed) .	1·570	·0157	100
" (hard) . .	1·608	·0160	98·1
Silver (annealed) . .	1·492	·0149	105
" (hard) . . .	1·620	·0162	98
Gold	2·077	·0208	76
Aluminium (annealed)	2·889	·0289	54
Platinum . . .	8·982	·0898	17
Iron (pure) . . .	9·638	·0964	16
Iron (telegraph wire) .	15	·15	10
Lead	19·63	·1963	8·3
Mercury . . .	94·34	·9434	1·6
Selenium . . .	6×10^{10}		$\frac{1}{40{,}000{,}000{,}000}$
Carbon (graphite) .	2400 to 42000		
" (arc light) .	about 4000		$\frac{1}{2500}$
Alloys.			
German-silver . . (Cu 60, Zn 26, Ni 14)	20·76	·2076	7·6
Platinum-silver . . (Pt 67, Ag 33)	2·4	·024	6·5
Platinoid . . . (Cu 59, Zn 25·5, Ni 14, W 55)	32·5	·325	4·8
Manganin . . . (Cu 84, Ni 12, Mn 3·5)	47·5	·475	3·3
Liquids at 18° C.			
Pure water . . .	$26{\cdot}5 \times 10^{8}$		less than one millionth part
Dilute H_2SO_4, 5% .	486×10^{4}		
" H_2SO_4, 30% .	137×10^{4}		
" H_2SO_4, 80% .	918×10^{4}		
" $ZnSO_4$, 24% .	214×10^{5}		
" HNO_3, 30% .	129×10^{4}		
Insulators.			
Glass at 20° C. . .	91×10^{18}		
Glass at 200° C. . .	$22{\cdot}7 \times 10^{12}$		less than one billionth
Guttapercha 24° C. .	$4{\cdot}5 \times 10^{20}$		

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supports of stoneware, porcelain, or glass on which telegraph wires are carried (Art. 497).

406. Typical Circuit. — Let us consider the typical case of the circuit shown in Fig. 207, in which a battery, ZC, is joined up in circuit with a galvanometer by means of wires whose resistance is R. The total electromotive-force of the battery we will call E, and the total internal resistance of the liquids in the cells *r*. The resistance of the galvanometer coils may be called G. Then, by Ohm's law: —

$$C = \frac{E}{R + r + G}.$$

The *internal resistance r* of the liquids of the battery bears an important relation to the *external resistance* of the circuit (including R and G), for on this relation depends the best way of arranging the battery cells. Suppose, for example, that we have a battery of 50 small Daniell's cells at our disposal, of which we may reckon the electromotive-force as one volt (or, more accurately, 1·07 volt) each, and each having an internal resistance of two ohms. If we have to use these cells on a circuit where there is already of necessity a high resistance, we should couple them up "in series" rather than in parallel. For, supposing we have to send our current through a line of telegraph 100 miles long, the external resistance R will be (reckoning 13 ohms to the mile of wire) at least 1300 ohms. Through this resistance a single such cell would give a current of less than one milliampere, for here E = 1, R = 1300, *r* = 2, and therefore $C = \frac{E}{R + r} = \frac{1}{1300 + 2} = \frac{1}{1302}$ of an ampere, a current far too weak to work a telegraph instrument.

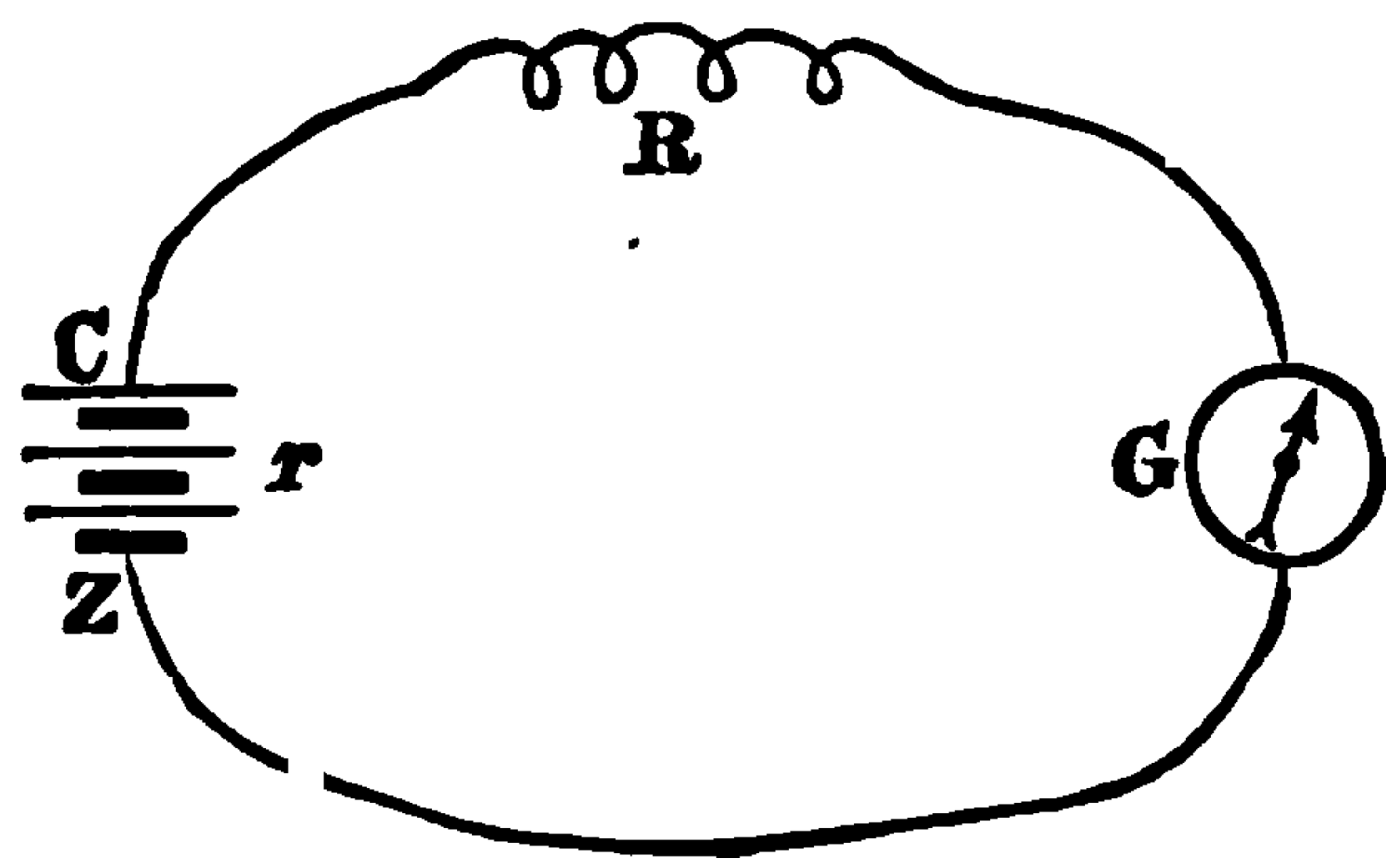


Fig. 207.

With fifty such cells in series we should have $E = 50$, $r = 100$, and then

$C = \frac{50}{1300 + 100} = \frac{50}{1400} = \frac{1}{28}$ of an ampere, or over 35 milli-amperes. In telegraph work, where the instruments require a current of 5 to 10 milli-amperes to work them, it is usual to reckon an additional Daniell's cell for every 5 miles of line, each instrument in the circuit being counted as having as great a resistance as 10 miles of wire.

If, however, the resistance of the external circuit be small, such arrangements must be made as will keep the total internal resistance of the battery small. Suppose, for example, we wish merely to heat a small piece of platinum wire to redness, and use stout copper wires to connect it with the battery. Here the external resistance may possibly not be as much as 1 ohm. In that case a single cell would give a current of $\frac{1}{3}$ of an ampere (or 333 milli-amperes) through the wire, for here $E = 1$, $R = 1$, and $r = 2$. But 10 cells would only give half as much again, or 476 milli-amperes, and fifty cells only 495 milli-amperes, and with an infinite number of such cells *in series* the current could not possibly be more than 500 milli-amperes, because every cell, though it adds 1 to E, adds 2 to R. It is clear then that though linking many cells *in series* is of advantage where there is the resistance of a long line of wire to be overcome, yet where the external resistance is small the practical advantage of adding cells in series soon reaches a limit.

But suppose in this second case, where the external resistance of the circuit is small, we reduce also the internal resistance of our battery by linking cells together *in parallel*, joining several zincs of several cells together, and joining also their copper poles together (as suggested in Art. 192), a different and better result is attained. Suppose we thus join up four cells. Their electromotive-force will be no more, it is true, than that

of one cell, but their resistance will be but $\frac{1}{4}$ of one such cell, or $\frac{1}{2}$ an ohm. These four cells would give a current of 666 milli-amperes through an external resistance of 1 ohm, for if $E = 1$, $R = 1$, and the internal resistance be $\frac{1}{4}$ of r, or $= \frac{1}{2}$, then

$$C = \frac{E}{R + r} = \frac{2}{3} \text{ of an ampere, or 666 milli-amperes.}$$

If we arrange the cells of a battery in n files of m cells in series in each file (there being $m \times n$ similar cells altogether), the electromotive-force of each file will be m times the electromotive-force E of each cell, or mE; and the resistance of each file will be m times the resistance r of each cell, or mr. But there being n files in parallel the whole internal resistance will be only $\frac{1}{n}$ of the resistance of any one file, or will be $\frac{m}{n}r$, hence, by Ohm's law, such a battery would give as its current

$$C = \frac{mE}{\frac{m}{n}r + R}.$$

407. Best Groupings of Cells.—If the question arises as to the best way of grouping a given number of cells, it must be replied that there are several best ways.

(1) *Grouping for best Economy.*—So group the cells that their united internal resistance shall be *very small* compared with the external resistance. In this case the materials of the battery will be consumed slowly, and the current will not be drawn off at its greatest possible strength; but there will be a minimum waste of energy (Art. 435).

(2) *Grouping for greatest Current.*—It can be shown mathematically that, for a given battery of cells, the way of grouping them that will give the largest steady current when they are required to work through a given external resistance R, is so to choose m and n that *the internal resistance* $\left(\frac{m}{n}r\right)$ *shall equal the external resistance.* The

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at B, the current will also be divided, part flowing through one branch, part through the other. Any branch which serves as a by-pass to another branch is termed a *shunt*. *The relative strengths of current in the two branches* will be proportional to their conductances, *i.e. inversely proportional to their resistances.** Thus, if r be a wire of 2 ohms resistance and r' 3 ohms, then current in r : current in $r' = r' : r = 3 : 2$, or, $\frac{3}{5}$ of the whole current will flow through r, and $\frac{2}{5}$ of the whole current through r'.

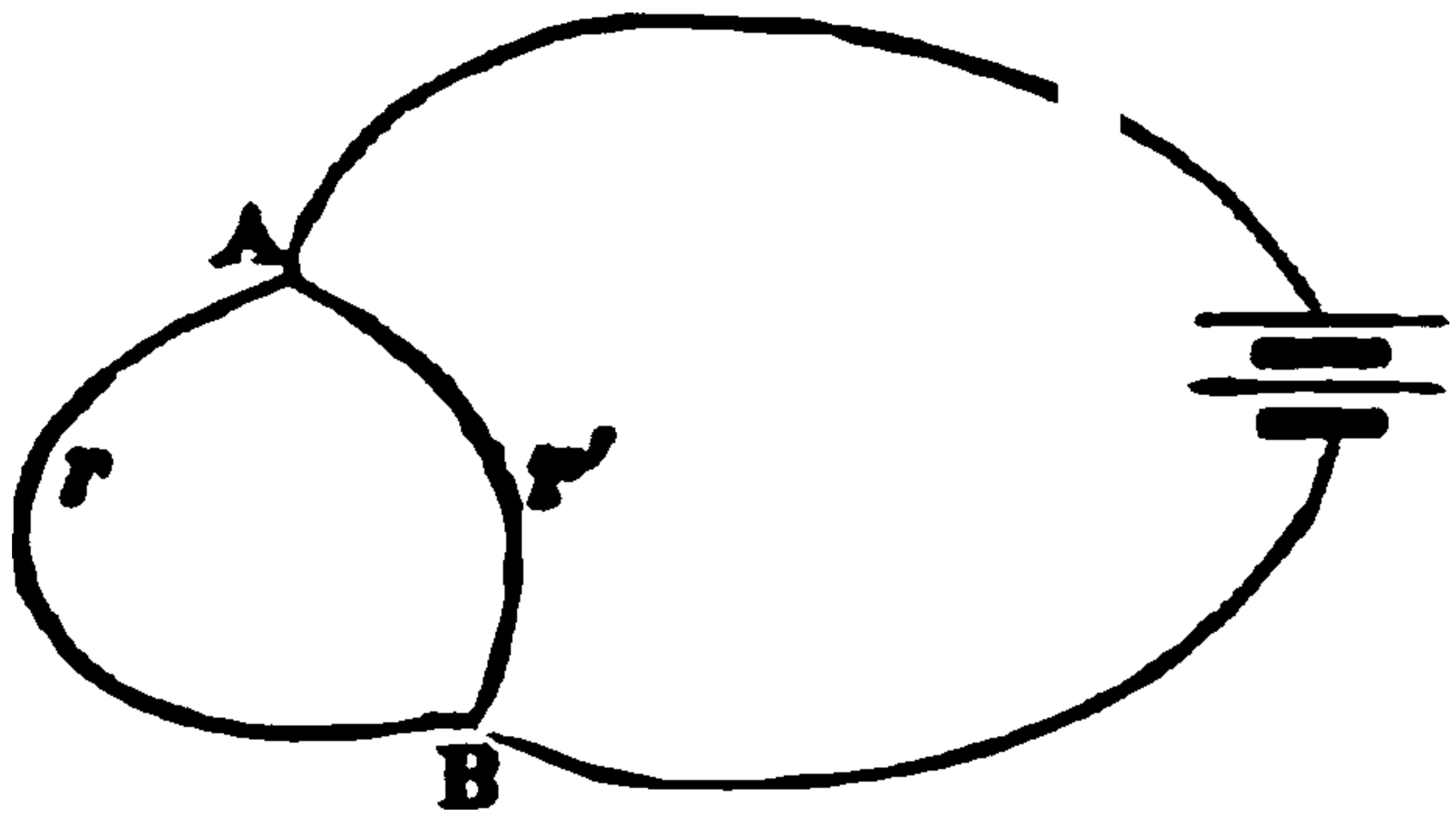


Fig. 208.

The *joint resistance* of the divided circuit between A and B will be less than the resistance of either branch singly, because the current has now two paths. In fact, the joint conductance will be the sum of the two separate conductances. And if we call the joint resistance R, it follows that

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'} = \frac{r' + r}{rr'},$$

whence $R = \dfrac{rr'}{r' + r}$, or, in words, *the joint resistance of a divided conductor is equal to the product of the two separate resistances divided by their sum.* This is sometimes called *the law of shunts*, because each of the branches may be regarded as a shunt to the other. A simple construction for finding the value graphically is given in Fig. 209. Let lines representing the two resistances r and r' be erected at the ends of any base line, and the diagonals

* There is a popular fallacy that an electric current "always takes the line of least resistance." It never does, though *part* of the current may flow that way. It divides between the various paths in proportion to their easiness. It is only spark discharges which pierce a non-conductor that can be said to take the line of least resistance.

drawn as shown. The perpendicular at the point of their intersection will be the joint resistance R.

In case there are three or more branches all in parallel, as in Fig. 210, the rule may be generalized as follows:—

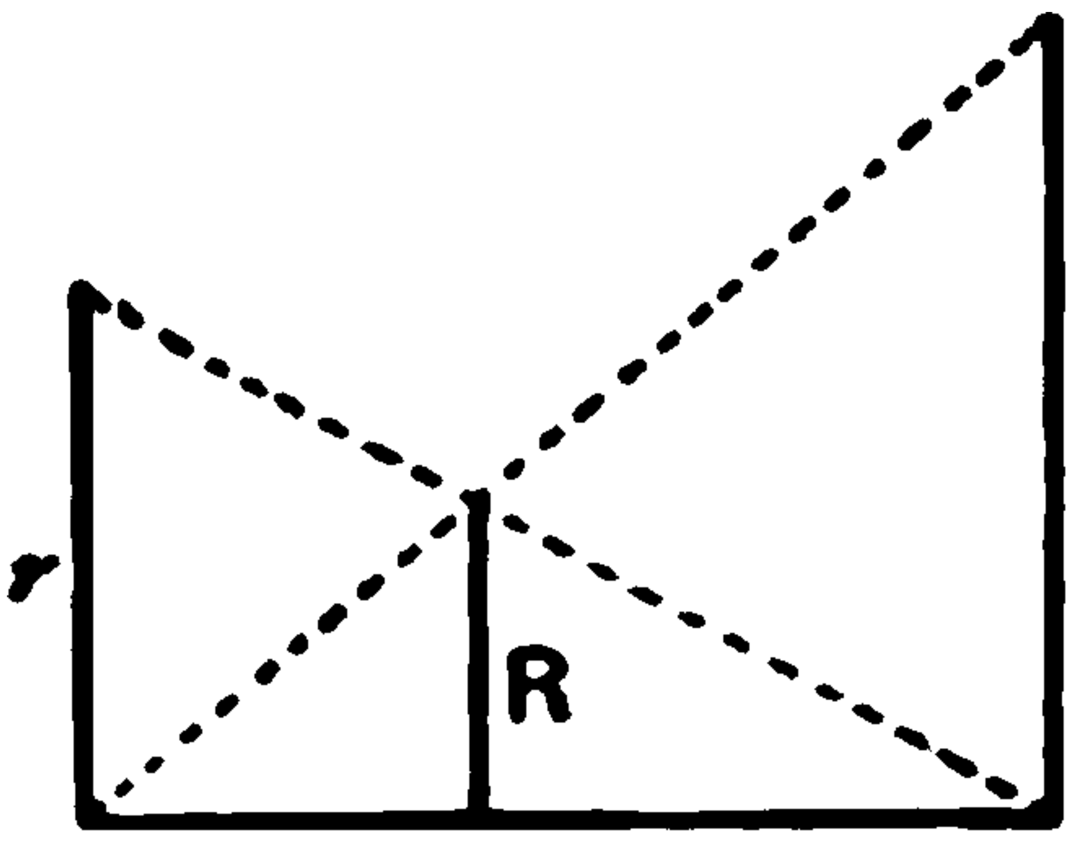


Fig. 209.

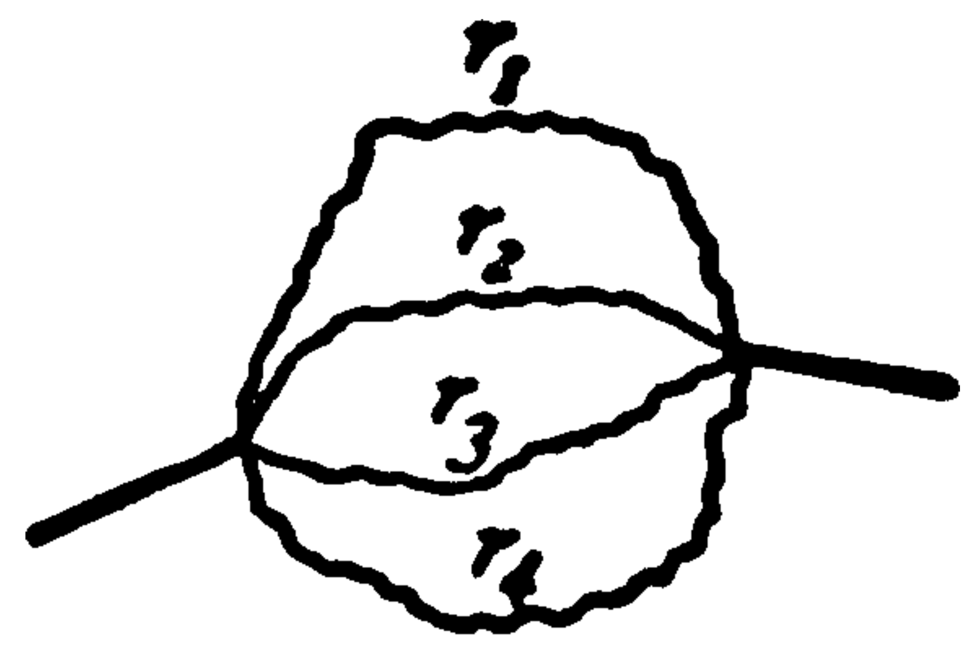


Fig. 210.

The joint resistance of any number of conductors in parallel is the reciprocal of the sum of the reciprocals of the separate resistances.

Kirchhoff has given the following important laws, both of them deducible from Ohm's law.

(i.) *In any branching network of wires the algebraic sum of the currents in all the wires that meet in any point is zero.*

(ii.) *When there are several electromotive-forces acting at different points of a circuit, the total electromotive-force round the circuit is equal to the sum of the resistances of its separate parts multiplied each into the strength of the current that flows through it.*

410. Current Sheets. — When a current enters a solid conductor it no longer flows in one line but spreads out and flows through the mass of the conductor. When a current is led into a thin plate of conducting matter it spreads out into a *current sheet* and flows through the plate by *stream-lines* in directions that depend upon the form of the plate and the position of the pole by which it returns to the battery. Thus, if wires from the two poles of a battery are brought into contact with two neighbouring

points A and B in the middle of a very large flat sheet of tinfoil, the current flows through the foil not in one straight line from A to B, but in stream-lines, which start out in all directions from A, and curl round to meet in B, in curves very like those of the "lines of force" that run from the N pole to the S pole of a magnet (Fig. 67). When the earth is used as a return wire to conduct the telegraph currents (Fig. 274), a similar spreading of the currents into current sheets occurs.

LESSON XXXIV. — *Electrical Measurements*

411. Measurement of Resistance. — The practical electrician has to measure electrical resistances, electromotive-forces, and the capacities of condensers. Each of these several quantities is measured by comparison with ascertained standards, the particular methods of comparison varying, however, to meet the circumstances of the case. Only a few simple cases can be here explained.

Ohm's law shows us that the strength of a current due to an electromotive-force falls off in proportion as the resistance in the circuit increases.

(*a*) *Method of Substitution.* — It is therefore possible to compare two resistances with one another by finding out in what proportion each of them will cause the current of a constant battery to fall off. Thus, suppose in Fig. 207 we have a standard battery of a few Daniell's cells, joined up in circuit with a wire of an unknown resistance R, and with a galvanometer, we shall obtain a current of a certain strength, as indicated by the galvanometer needle experiencing a certain deflexion. If we remove the wire R, and substitute in its place in the circuit wires whose resistances we *know*, we may, by trying, find one which, when interposed in the path of the current, gives the same deflexion on the galvanometer. This wire and the one we called R offer equal resistance to the current. This

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of the differential galvanometer will show *no* deflexion. This null method is very reliable.

(*d*) *Bridge Method.*—The best of all the ways of measuring resistances is, however, with the important instrument known as Wheatstone's Bridge, described below in Art. 413.

(*e*) *Condenser Methods.*—To measure very high resistances the plan may be adopted of charging a condenser from a standard battery for a definite time through the resistance, and then ascertaining the accumulated charge by discharging it through a ballistic galvanometer (Art. 218). Or in another method the condenser is allowed to discharge itself slowly through the high resistance, and the time taken by the potential to fall through any given fraction of its original value is observed. This time is proportional to the resistance, to the capacity, and to the logarithm of the given fraction.

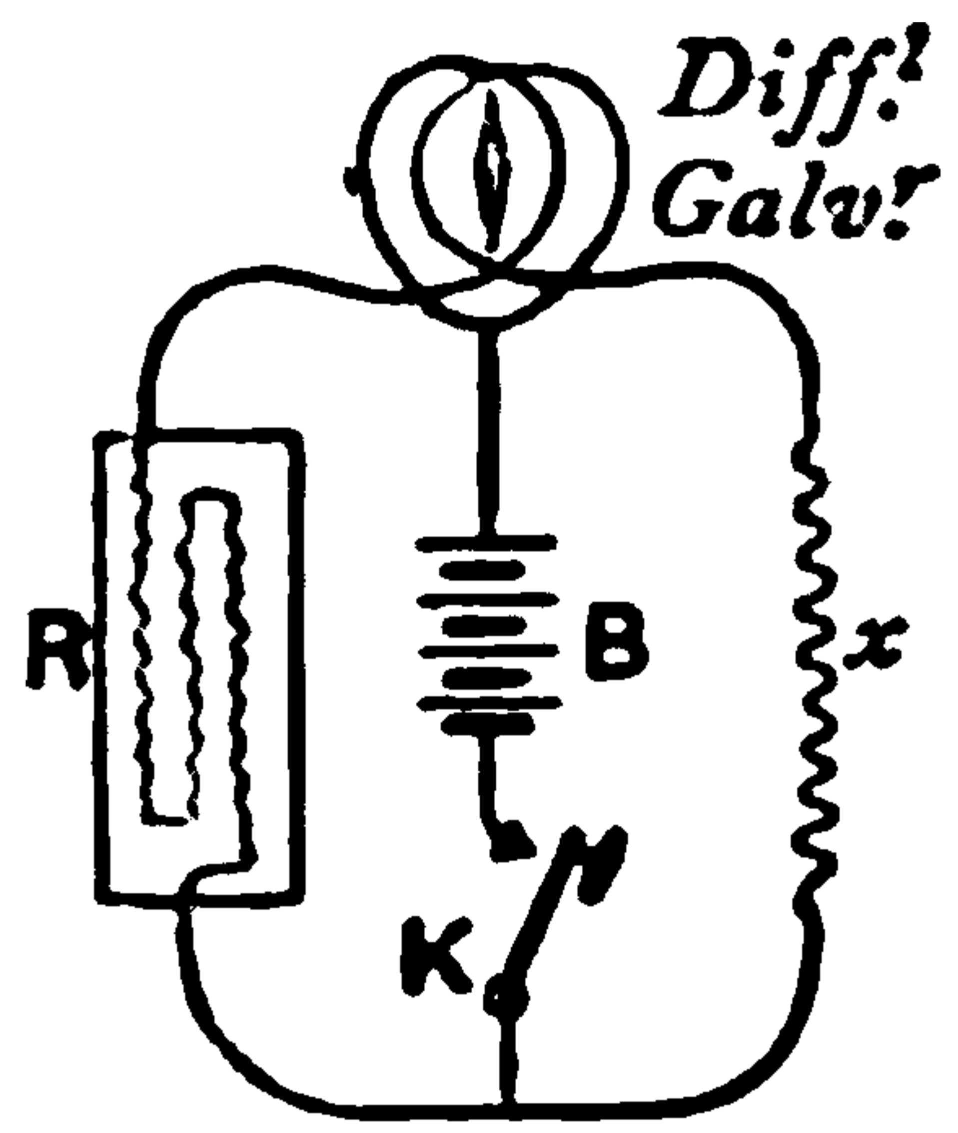


Fig. 211.

412. Fall of Potential along a Wire.—To understand the principle of Wheatstone's Bridge we must explain a preliminary point. If the electric potential of different points of a circuit be examined by means of an electrometer, as explained in Art. 289, it is found to decrease all the way round the circuit from the + pole of the battery, where it is highest, down to the −pole, where it is lowest. If the circuit consist of one wire of uniform thickness, which offers, consequently, a uniform resistance to the current, it is found that the potential falls uniformly; if, however, part of the circuit resists more than another, it is found that the potential falls most rapidly along the conductor of greatest resistance. If with a suitable voltmeter we explore the fall of potential between two points *a* and *b* of a circuit (Fig. 212), we shall find in every case the fall of potential proportional to the resistance

between those two points. For V = CR, and therefore, for the same C, the V across any part is proportional to the R of that part. We know, for example, that when we have gone round the circuit to a point where the potential has fallen through half its value, the current has at that point gone through half the resistances. The best way to measure a very large current is to measure (with sensitive voltmeter arrangement of galvanometer) the drop of potential it produces when sent through a known very low resistance such as a strip of platinoid having exactly $\frac{1}{1000}$ ohm resistance between two measured points. To measure a very small resistance, it should be put in series with another known very small resistance, and the drops of potential when the same current flows through both are compared: the resistance of each being as the drop in potential between its ends.

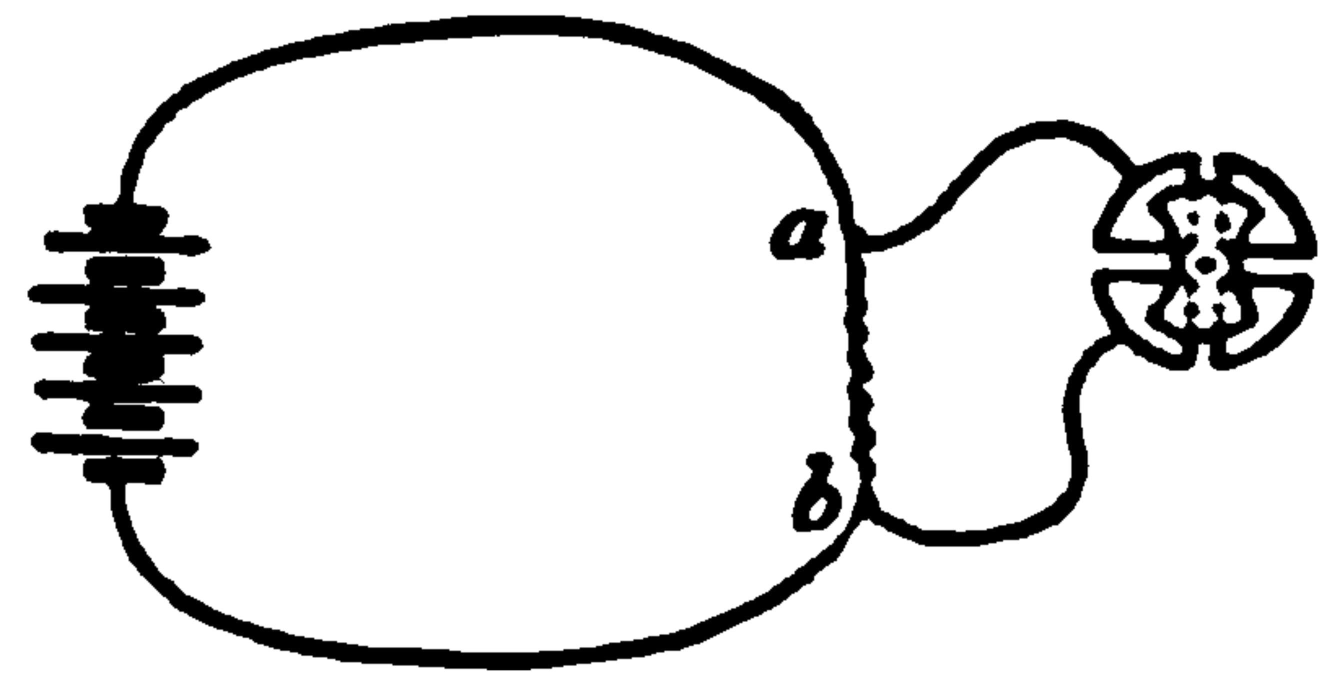


Fig. 212.

413. Wheatstone's Bridge.—This instrument, invented by Christie, and applied by Wheatstone to measure resistances, consists of a system of conductors shown in diagram in Fig. 213. This circuit of a battery is made to branch at P into two parts, which reunite at Q, so that part of the current flows through the point M, the other part through the point N. The four conductors D, C, B, A, are spoken of as the "arms" of the "balance" or "bridge"; it is by the proportion subsisting between their resistances that the resistance of one of them can be calculated when the resistances of the other three are known. When the current which starts from C at the battery arrives at P, the potential will have fallen to a certain value. The potential of the current in the upper branch again falls to M, and continues to fall to Q. The potential of the lower branch falls to N, and again falls till it reaches the value at Q. Now if N be the same

proportionate distance along the resistances between P and Q, as M is along the resistances of the upper line between P and Q, the potential will have fallen at N to the same value as it has fallen to at M; or, in other words, if the ratio of the resistance C to the resistance D

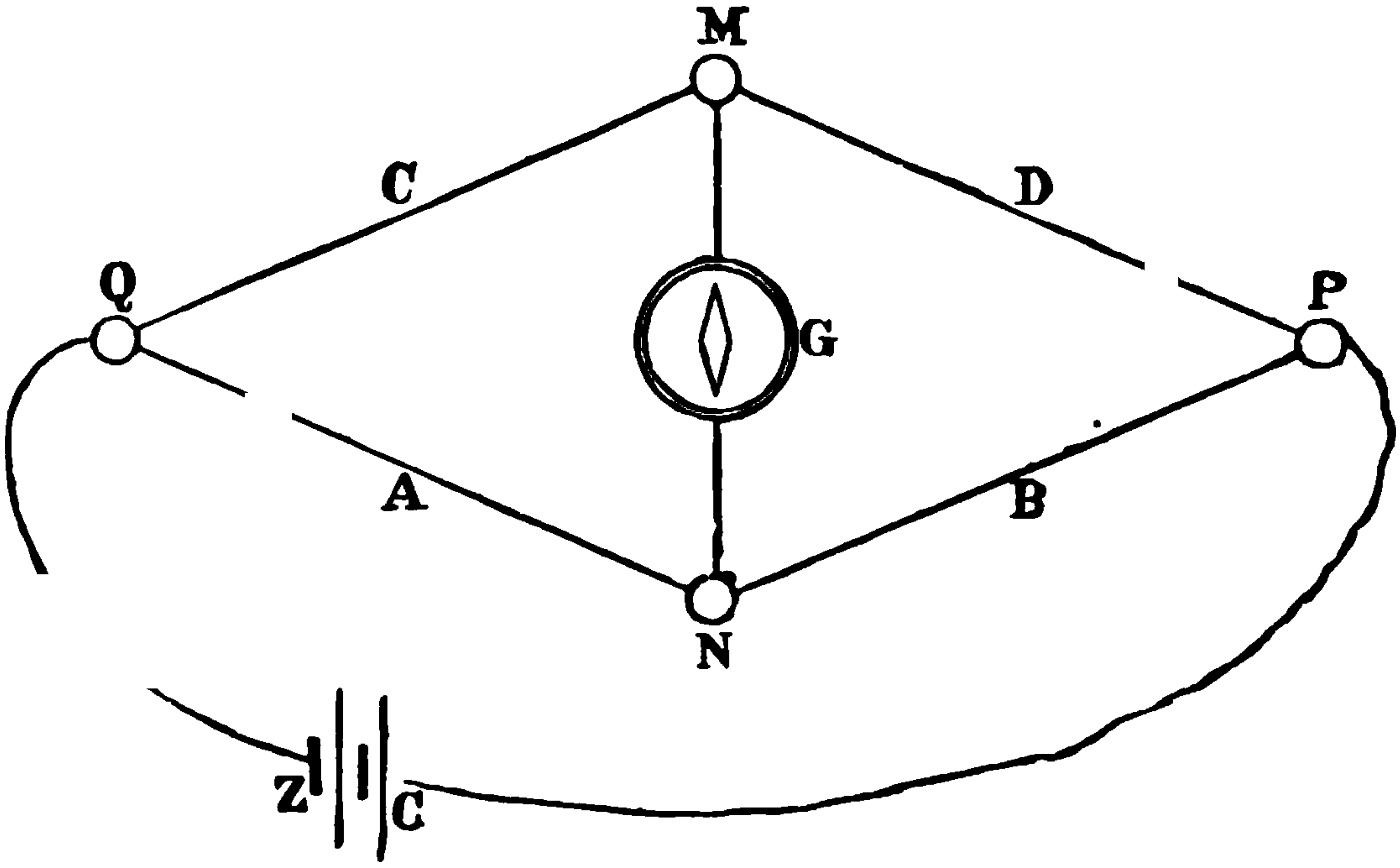


Fig. 218.

be equal to the ratio between the resistance A and the resistance B, then M and N will be at equal potentials. To find out whether they are at equal potentials a sensitive galvanometer is placed in a branch wire between M and N; it will show *no* deflexion when M and N are at equal potentials; or when the four resistances of the arms "balance" one another by being in proportion, thus:—

$$A : C :: B : D.$$

If, then, we know what A, B, and C are, we can calculate D, which will be

$$D = \frac{B \times C}{A}.$$

Example.—Thus if A and C are (as in Fig. 216) 10 ohms and 100 ohms respectively, and B be 15 ohms, D will be $15 \times 100 \div 10 = 150$ ohms.

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current flows through the solid brass pieces and plugs without encountering any serious resistance; but when any plug is removed, the current can only pass from the one brass piece to the other by traversing the coil thus thrown into circuit. The series of coils chosen is usually of the following numbers of ohms' resistance—1, 2, 2, 5; 10, 20, 20, 50; 100, 200, 200, 500; . . . up to 10,000 ohms. By pulling out one plug any one of these can be thrown into the circuit, and any desired whole

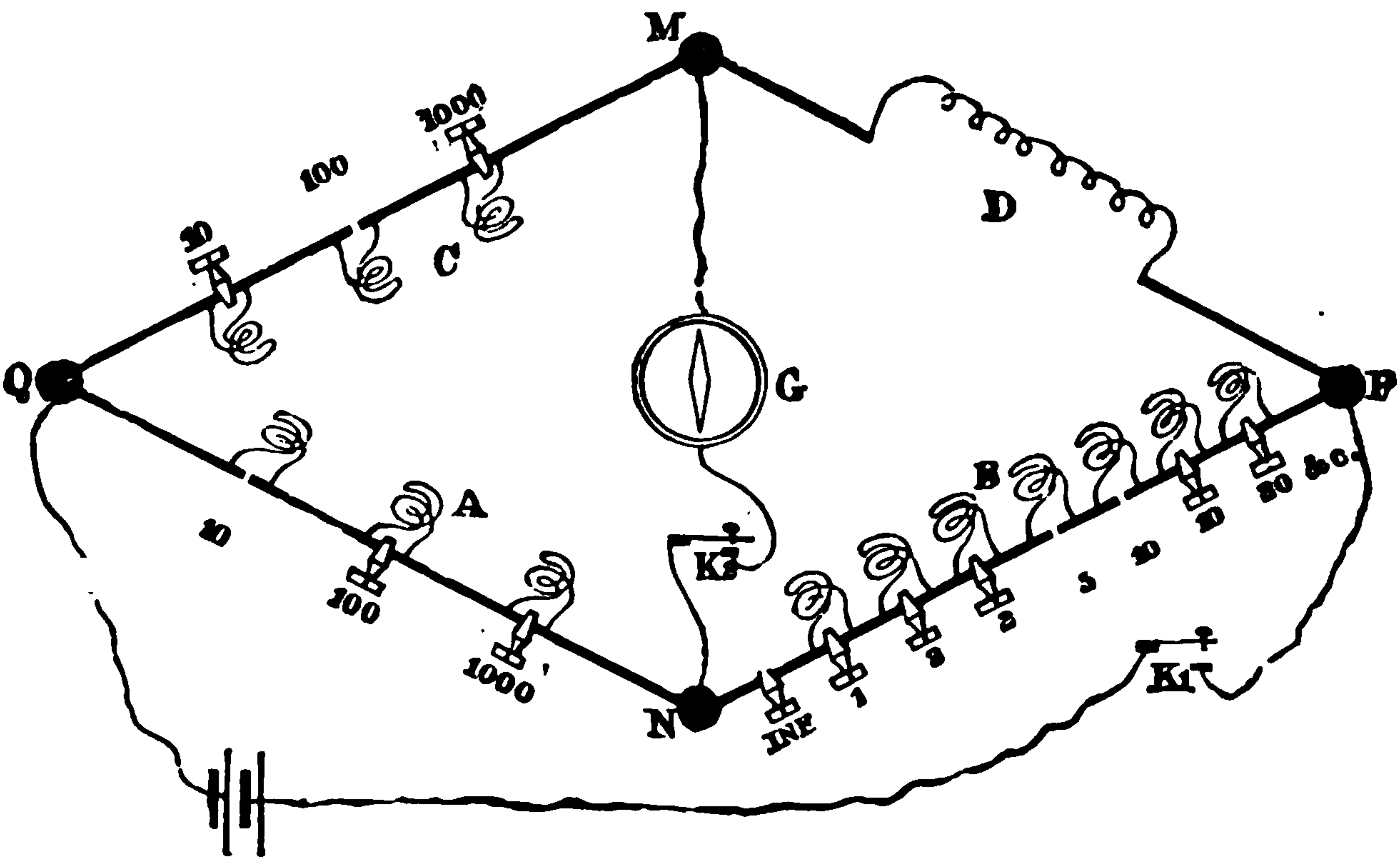


Fig. 216.

number, up to 20,000, can be made up by pulling out more plugs; thus a resistance of 263 ohms will be made up as 200 + 50 + 10 + 2 + 1 by unplugging those five coils.

It is usual to construct Wheatstone's bridges with some balancing resistance coils in the arms A and C, as well as with a complete set in the arm B. The advantage of this arrangement is that by adjusting A and C we determine the proportionality between B and D, and can, in certain cases, measure to fractions of an *ohm*. Fig. 216 shows a

more complete scheme, in which resistances of 10, 100, and 1000 ohms are included in the arms A and C.

Example.—Suppose we had a wire, whose resistance we knew to be between 46 and 47 ohms, and wished to measure the fraction of an ohm, we should insert it at D, and make A 100 ohms and C 10 ohms; in that case D would be balanced by a resistance in B 10 times as great as the wire D. If, on trial, this be found to be 464 ohms, we know that $D = 464 \times 10 \div 100 = 46{\cdot}4$ ohms.

415. Other Patterns of Bridge.—In practice the bridge is seldom or never made in the lozenge-shape of the diagrams.

Post-Office Bridge.—The resistance-box of Fig. 215 is, in itself, a complete "bridge" of the post-office pattern, the appropriate connexions being made by screws at various points. In using the bridge the battery circuit should always be completed by depressing the key K_1 before the key K_2 of the galvanometer circuit is depressed, in order to avoid the sudden violent "throw" of the galvanometer needle, which occurs on closing circuit in consequence of self-induction (Art. 458).

Dial Bridge.—To avoid errors arising from the different numbers of plugs in use, the coils of a bridge are sometimes arranged in dials—the units in one, the tens of ohms in another, and so forth—each dial having but one plug, or a movable arm like Fig. 206.

Metre Bridge.—This is a simple form very useful for measuring resistances not exceeding a few hundred ohms. Upon a long board is stretched over a scale one metre long a uniform thin wire of German-silver or other alloy, its ends being joined to stout pieces of copper. A, B, C, and D are four resistances joined as shown by stout strips of copper. When the wire from the galvanometer is slid along the wire to such a point that there is no current, it follows that

$$A + a : B + b = C : D.$$

Foster's method of measuring *small differences of resistance* is to get balance at a certain point along the wire, then interchange A and B, and again get balance at another point. The resistance of the piece of wire be-

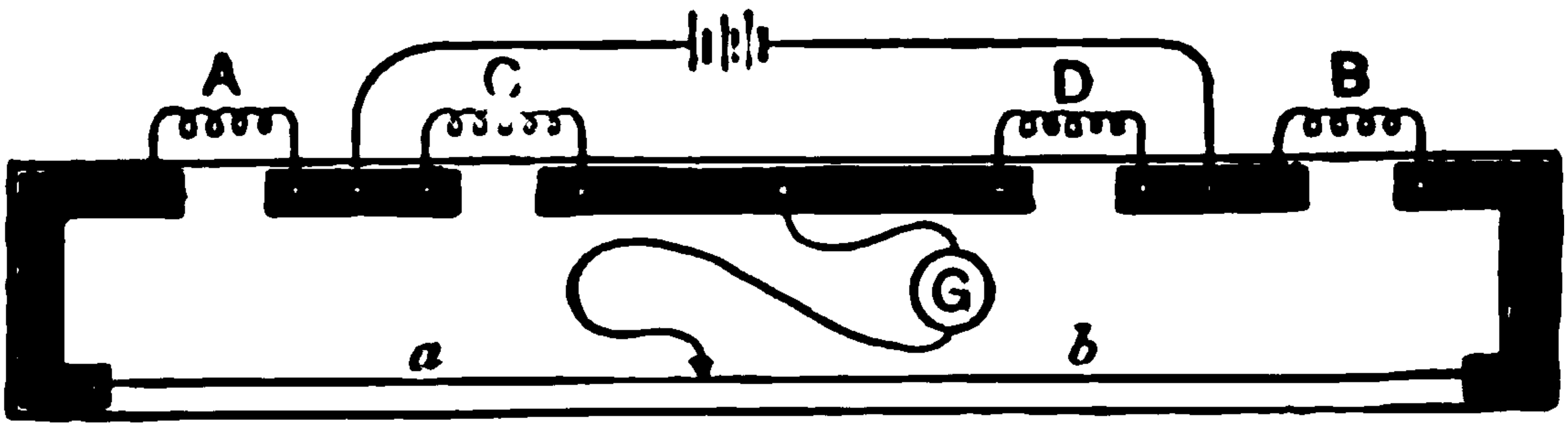


Fig. 217.

tween the two points will then be equal to the *difference* of the resistances A and B.

In a simpler way of using the bridge, A and B are replaced by strips of no appreciable resistance, so that

$$a : b :: \mathrm{C} : \mathrm{D}.$$

If D is the unknown resistance and C a known resistance, the *ratio* of the lengths a and b at once enables the unknown resistance to be calculated.

For further details of bridge methods consult Gray's *Absolute Measurements in Electricity and Magnetism*, Kempe's *Electrical Measurement*, or Ayrton's *Practical Electricity*.

416. **Measurement of Electromotive-Force.**—There being no easy absolute method of measuring electromotive-forces, they are usually measured *relatively*, by comparison with the electromotive-force of a standard cell, such as Clark's (Art. 188). The methods of comparison are various; only five are here mentioned.

(*a*) *Reduced Deflexion Method.*—Call E the electromotive-force of the battery to be measured, and E′ that of a standard battery. Join E with a galvanometer, and let it produce a deflexion of δ_1 degrees through the resist-

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such that the galvanometer shows that the Clark cell is balanced. Then connect the cell X whose E.M.F. is to be measured, and slide its contact along the wire until it also is balanced. Suppose it balances at 1024 of the scale, its E.M.F. will be 1·024. A single galvanometer will suffice if the wire to X is joined in between G and the Clark cell.

(*c*) *Voltmeter Method.* — If a galvanometer be constructed so that the resistance of its coils is several thousand ohms (in comparison with which the internal resistance of a battery or dynamo machine is insignificant), it will serve to measure electromotive-forces; for the strength of current through it will depend only on the electromotive-force between the ends of the coil. (See Art. 220 on Voltmeters.)

(*d*) *Condenser Method.* — A condenser of known capacity is charged from a standard cell, and then discharged through a ballistic galvanometer (Art. 218). The cell to be compared is then substituted for the standard cell. The E.M.F. is proportional to the throw of the galvanometer.

(*e*) *Electrometer Method.* — The electromotive-force of a battery may be measured directly as a difference of potentials by a quadrant electrometer. In this case the circuit is never closed, and no current flows.

417. Measurement of Internal Resistance of Cells. — This may be done in several ways.

(*a*) *Condenser Method.* — As in (*d*) of preceding Article, observe throw of galvanometer from condenser charged by the cell. Then shunt the cell with a suitably high resistance R and take another charge and discharge. If the two throws are called d_1 and d_2, the internal resistance will be $= R(d_1 - d_2)/d_2$.

(*b*) *Half-deflexion Method.* — Place the cell in series with a galvanometer the resistance of which is G, and a resistance-box in which there is unplugged a resistance R such that the deflexion is conveniently large. Now in-

crease the resistance in the box until it is seen by the deflexion that the current has been reduced to half what it was. If this added resistance is called a, then by Ohm's law it follows that the internal resistance is $= a - (R + G)$. This method is suitable for very high internal resistances.

(*c*) *Method of Opposition.* — Take two similar cells and join them in opposition to one another, so that they send no current of their own. Then measure their united resistance just as the resistance of a wire is measured. The resistance of one cell will be half that of the two.

(*d*) *Mance's Method.* — Place the cell itself in one arm of the Wheatstone's bridge, and put a *key* where the battery usually is, adjust the resistances till the permanent galvanometer deflexion is the same whether the key be depressed or not. When this condition of things is attained the battery resistance is balanced by those of the other three arms. (*Not a reliable method.*)

(*e*) *Alternate Current Method.* — If greater accuracy is required in the opposition method, the cells in opposition may be placed in one of the arms of a Wheatstone's bridge in which instead of the usual battery is inserted the secondary coil of a small induction coil (without condenser), and with which a telephone receiver is used instead of a galvanometer. The ceasing of the buzzing in the telephone corresponds to nul deflexion. By this means we avoid the disturbance of the balance of the opposing cells which occurs if continuous currents are used. This method is also excellent for measuring resistances of liquids.

418. Measurement of Capacity. — The capacity of a condenser may be measured by comparing it with the capacity of a standard condenser — such as the $\frac{1}{3}$ microfarad condenser (Fig. 159) — in one of the following ways: —

(*a*) *Electrometer Method.* — Charge the condenser of unknown capacity to a certain potential; then make it share its charge with the condenser of known capacity, and measure the potential to which the charge sinks; then calculate the original capacity, which will bear the same ratio to the joint capacity of the two as the final potential bears to the original potential.

(*b*) *Ballistic Galvanometer Method.* — Charge each condenser to equal differences of potential from the same cell or battery, and then discharge each successively through a ballistic galvanometer (Art. 188). The throw of the needle will be proportional in each case to the charge, and therefore to the capacity.

The law of the ballistic galvanometer is: —

$$KV = Q = \frac{H}{G} \times \frac{T}{\pi} \sin \tfrac{1}{2} \alpha,$$

where Q is the quantity of electricity (in C.G.S. units), H the magnetic field, by the constant of the galvanometer, T the period of one complete swing of the needle, and α the angle of first swing. The factor H/G may be eliminated by passing a steady current C to produce a steady deflexion β; when

$$C = \frac{H}{G} \tan \beta.$$

Combining this with the preceding, we have

$$Q = \frac{CT \sin \tfrac{1}{2} \alpha}{\pi \tan \beta}.$$

If α and β are both small this becomes

$$Q = CT\,\alpha/2\,\pi\beta.$$

If C is in amperes, Q will be in coulombs.

(*c*) *Bridge Method.* — Connect the two condensers K_1 and K_2 in two arms of a Wheatstone's bridge and adjust

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CHAPTER VII

THERMO-ELECTRICITY

Lesson XXXV. — *Thermo-Electric Currents*

419. Seebeck Effect. — In 1822 Seebeck discovered that a current may be produced in a closed circuit by heating a point of contact of two dissimilar metals. If a piece of bismuth and a piece of antimony be soldered together, and their free ends connected with a short-coil galvanometer, it is found that if the junction be warmed to a temperature higher than that of the rest of the circuit, a current flows in the direction from bismuth to antimony across the heated point; the current being proportional to the excess of temperature. If the junction is cooled below the temperature of the rest of the circuit a current in the opposite direction is observed. The electromotive-force thus set up will maintain the current so long as the excess of temperature of the heated point is kept up; heat being all the while absorbed in order to maintain the energy of the current. Such currents are called **Thermo-electric currents**, and the electromotive-force producing them is known as *Thermo-electromotive-force.*

420. Peltier Effect. — In 1834 Peltier discovered a phenomenon which is the converse of that discovered by Seebeck. He found that if a current of electricity from a battery be passed through a junction of dissimilar

metals the junction is either heated or cooled, according to the direction of the current. Thus a current which passes through a bismuth-antimony pair in the direction from bismuth to antimony absorbs heat in passing the junction of these metals, and cools it; whereas, if the current flow from antimony to bismuth across the junction it evolves heat, and the junction rises in temperature. It is clear that if bismuth is positive with respect to antimony, any current that may be caused to flow from bismuth to antimony is aided by the electromotive-force at that junction: whilst any current flowing from antimony to bismuth will meet with an opposing electromotive-force. In the latter case the current will do work

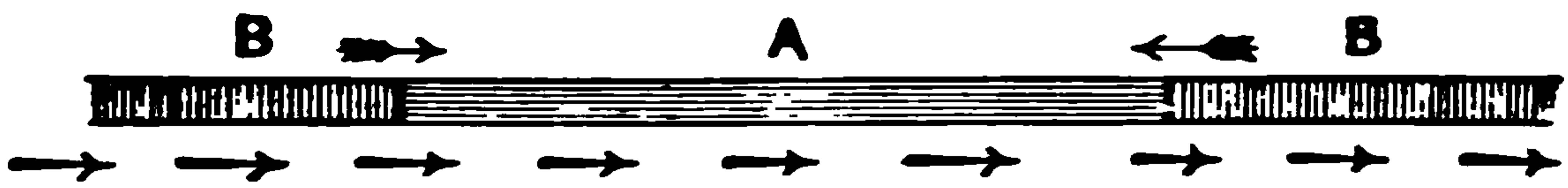


Fig. 220.

and heat the junction; in the former the current will receive energy at the expense of the junction, which will give up heat. In Fig. 220, the feathered arrows at the junctions represent the Peltier electromotive-forces, and the plain arrows the direction of the current.

This phenomenon of heating (or cooling) by a current, where it crosses the junction of two dissimilar metals (known as the "Peltier effect," to distinguish it from the ordinary heating of a circuit where it offers a resistance to the current, which is sometimes called the "Joule effect"), is utterly different from the evolution of heat in a conductor of high resistance, for (*a*) the Peltier effect is *reversible*; the current heating or cooling the junction according to its direction, whereas a current meeting with resistance in a thin wire heats it in whichever direction it flows; and (*b*) the amount of heat evolved or absorbed in the Peltier effect is proportional simply to the current, not to the *square* of the current as the heat of resistance is.

The complete law of the heat developed in a circuit will therefore require to take into account any Peltier effects which may exist at metal junctions in the circuit. If the letter P stand for the difference of potential due to the heating of the junction, expressed as a fraction of a volt, then the complete law of heat is

$$U = 0{\cdot}24 \times (C^2Rt \pm PCt),$$

which the student should compare with Joule's law in Art. 427. The quantity called P is also known as *the coefficient of the Peltier effect*; it has different values for different pairs of metals, and is numerically equal to the number of *ergs* of work which are evolved as heat at a junction of the particular metals by the passage of one absolute unit (10 *coulombs*) of electricity through the junction.

421. Thermo-electric Laws. — The thermo-electric properties of a circuit are best studied by reference to the simple circuit of Fig. 221, which represents a bismuth - antimony pair united by a copper wire. If all parts of the circuit are at one temperature, even though there may be at the junctions electromotive-forces as suggested above, there will be no current, since the electromotive-forces are in equilibrium. But when a junction is heated this equilibrium no longer exists, and there will be a resultant electromotive-force. It is found to obey the following laws: —

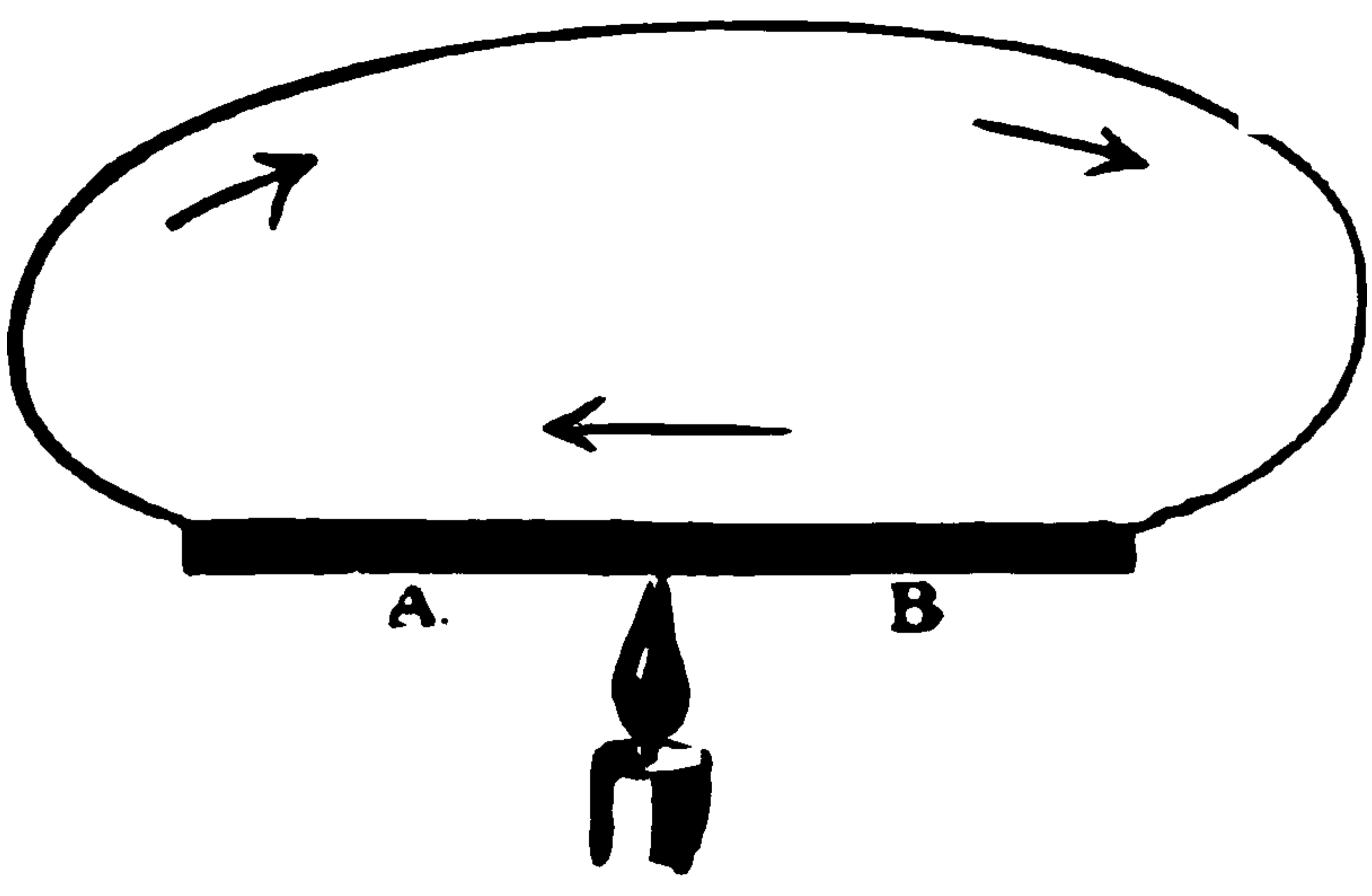


Fig. 221.

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That of the more powerful bismuth-antimony pair is for 1° C., about 117 microvolts. Thermo-electric power varies, however, with temperature: for example, that of iron is really – 17·5 + 0·049*t* (where *t* is the mean temperature of the two junctions), iron becoming less negative when hot. Copper is – 1·36 – 0·01*t*, becoming more negative. There will be obviously one particular temperature or *neutral point*, at which their powers will be equal.

423. Thermo-electric Inversion.—Cumming discovered that in the case of iron and other metals an inversion of their thermo-electric properties may take place at a high temperature. In the case of the copper-iron pair the temperature of 275° is a neutral point; below that temperature the current flows through the hotter junction from the copper to the iron; but when the circuit is above that temperature iron is thermo-electrically positive to copper. The neutral point for a zinc-iron pair is about 200°. The inversion is easily shown by heating the junction of two long strips of these metals, riveted together in a V-form, and watching the effect on a galvanometer connected to their other ends. There will at first be a deflexion which will go on increasing until the temperature of 200° is attained, but on further heating the junction the deflexion diminishes and at about 400° reverses, the current flowing the other way. Fig. 222 shows graphically the curves obtained with iron-zinc and iron-copper pairs when one junction is kept at 0° while the other is heated. The dotted line is for the iron-zinc pair when one junction is kept at 50° and the other heated.

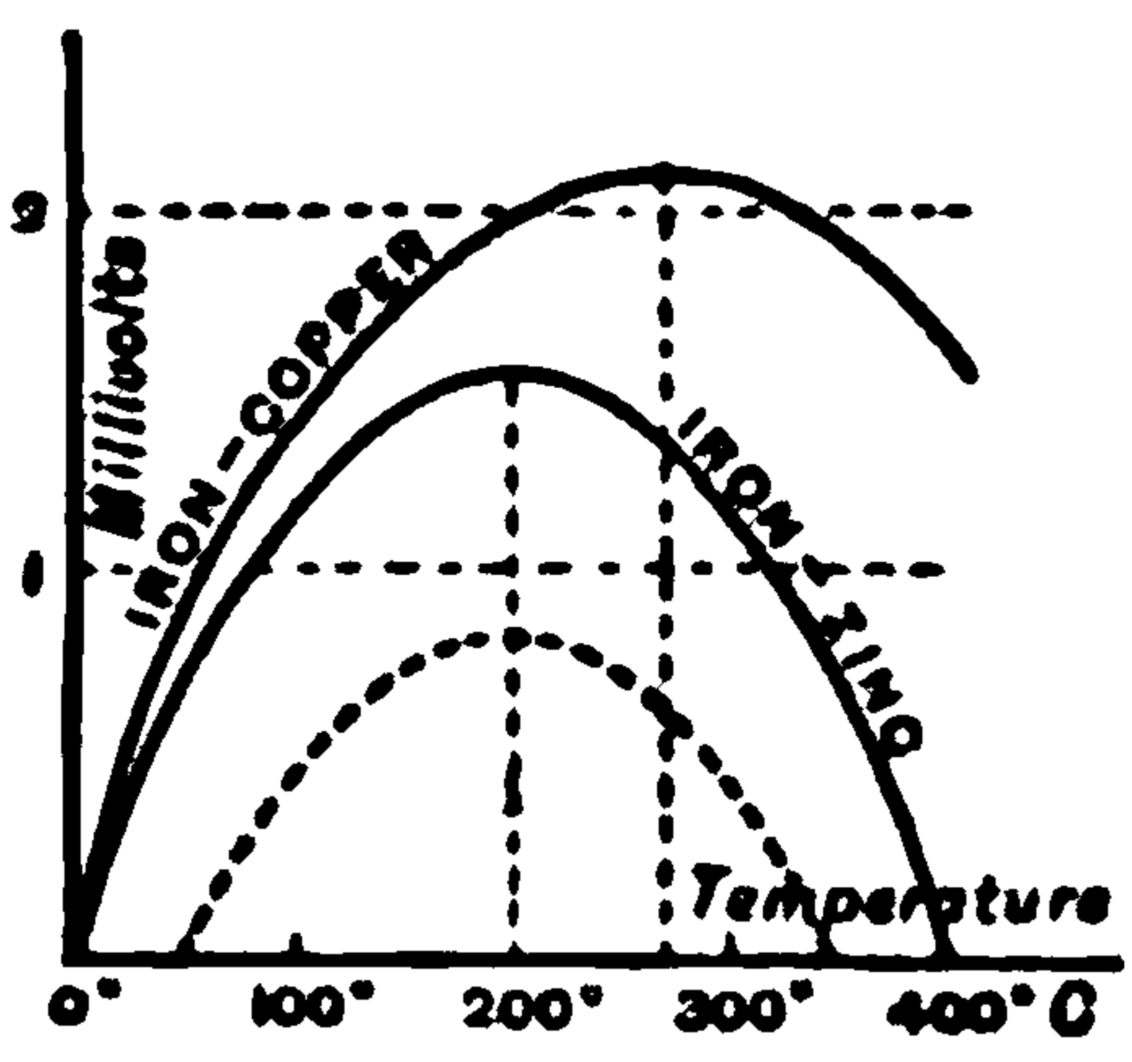


Fig. 222.

424. Thermo-electric Diagram.—The facts of thermo-electricity are best studied by means of the

diagrams suggested by Lord Kelvin and constructed by Professor Tait. In that given in Fig. 223 the horizontal divisions represent the temperatures; the vertical distances indicating the thermo-electric power, in microvolts per degree. These powers are measured with respect to the metal lead, which is taken as the standard of zero at all temperatures, because, while with other metals there

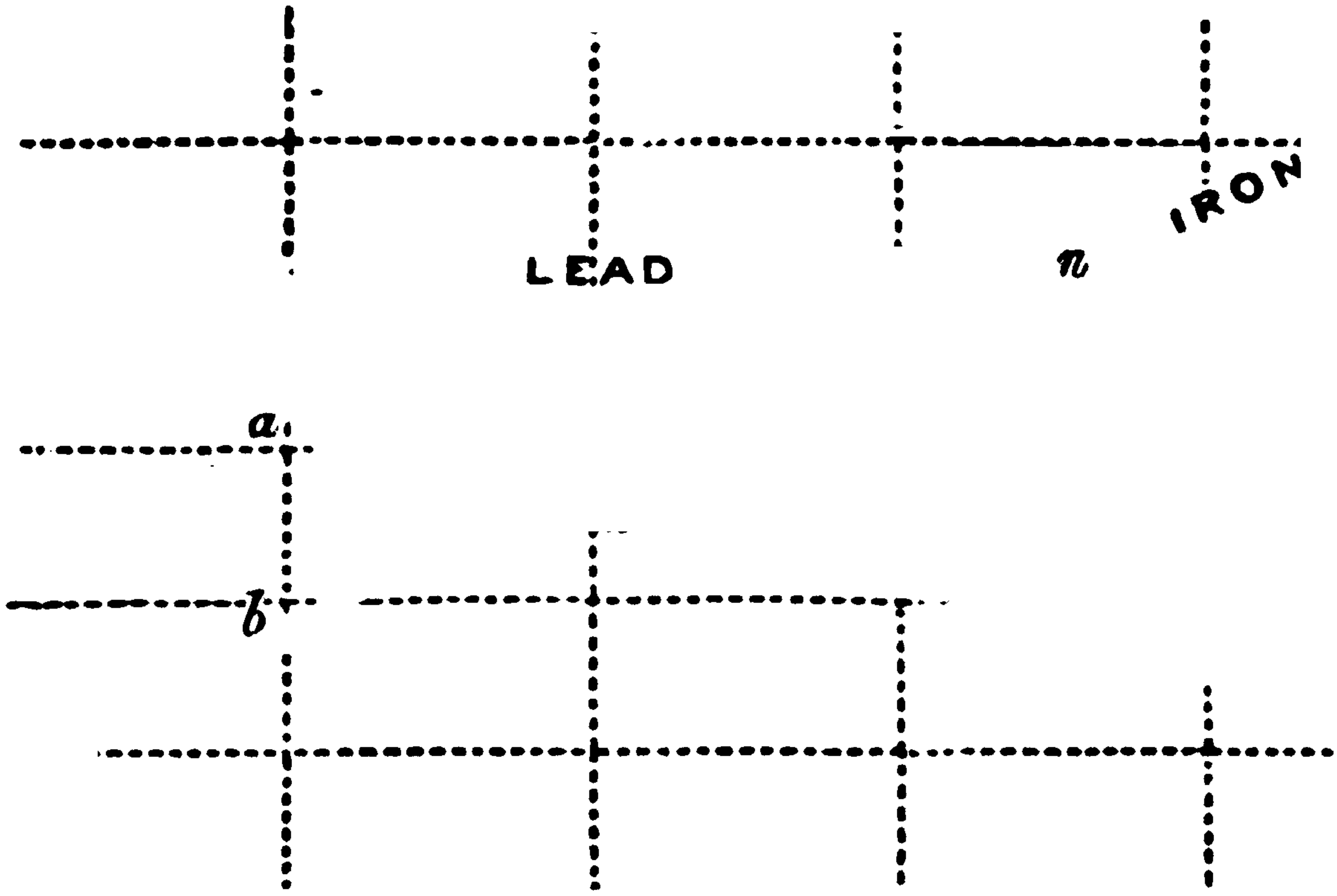


Fig. 223.

appears to be a difference of potentials between the metal hot and the same metal cold, hot lead brought into contact with cold lead shows no perceptible thermo-electric difference.

An example will illustrate the usefulness of the diagram. Let a circuit be made by uniting at both ends a piece of iron and a piece of copper; and let the two junctions be kept at 0° and 100° respectively by melting ice and boiling water. Then the total electromotive-force round the circuit is represented by the area *a*, 0, – 15, *b*.

The slope of the lines for the various metals represents the property referred to above, of an electromotive-force between differently-heated portions of the same metal accompanied by an absorption or evolution of heat when the current flows from a hotter to a colder portion of the same metal. This effect, known as the **Thomson effect** from its discoverer Sir W. Thomson (Lord Kelvin), is opposite in iron to what it is in copper or zinc. Copper when hot is negative compared with copper that is cold. Hence if a current is sent from a hot to a cold part of a piece of copper it encounters an opposing electromotive-force. Hence when a current of electricity flows from a hot to a cold point in copper it evolves heat; and it absorbs heat when it flows from a cold point to a hot point in the copper. In iron a current flowing from a hot point to a cold point absorbs heat.

The thermo-electromotive-force of a pair, of which the junctions are at temperatures T and t respectively, and of which n is the temperature of the neutral point, may be conveniently expressed by the following formula:—

$$E = p(T - t)\left\{1 - \frac{\frac{1}{2}(T + t)}{n}\right\};$$

where p is the volts per degree (at 0°) as given in the table (Art. 422).

425. Thermo-electric Piles. — The electromotive-force of a bismuth-antimony pair, when the junctions are kept at 0° and 100°, is only 0·0115 volt. In order to increase the electromotive-force of thermo-electric pairs it is usual to join a number of pairs of metals (preferably bismuth and antimony) in series, but so bent that the *alternate* junctions can be heated as shown in Fig. 224 at BBB, whilst the other set AAA are kept cool. The various electromotive-forces then all act in the same direction, and the current is increased in proportion to the number of pairs of junctions. Powerful thermo-electric batteries have been made by Clamond — an iron-

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proposed a thermo-galvanometer on this plan in 1835.

In the radio-micrometer of Vernon Boys (1889) a loop of wire, suspended by a delicate quartz fibre between the

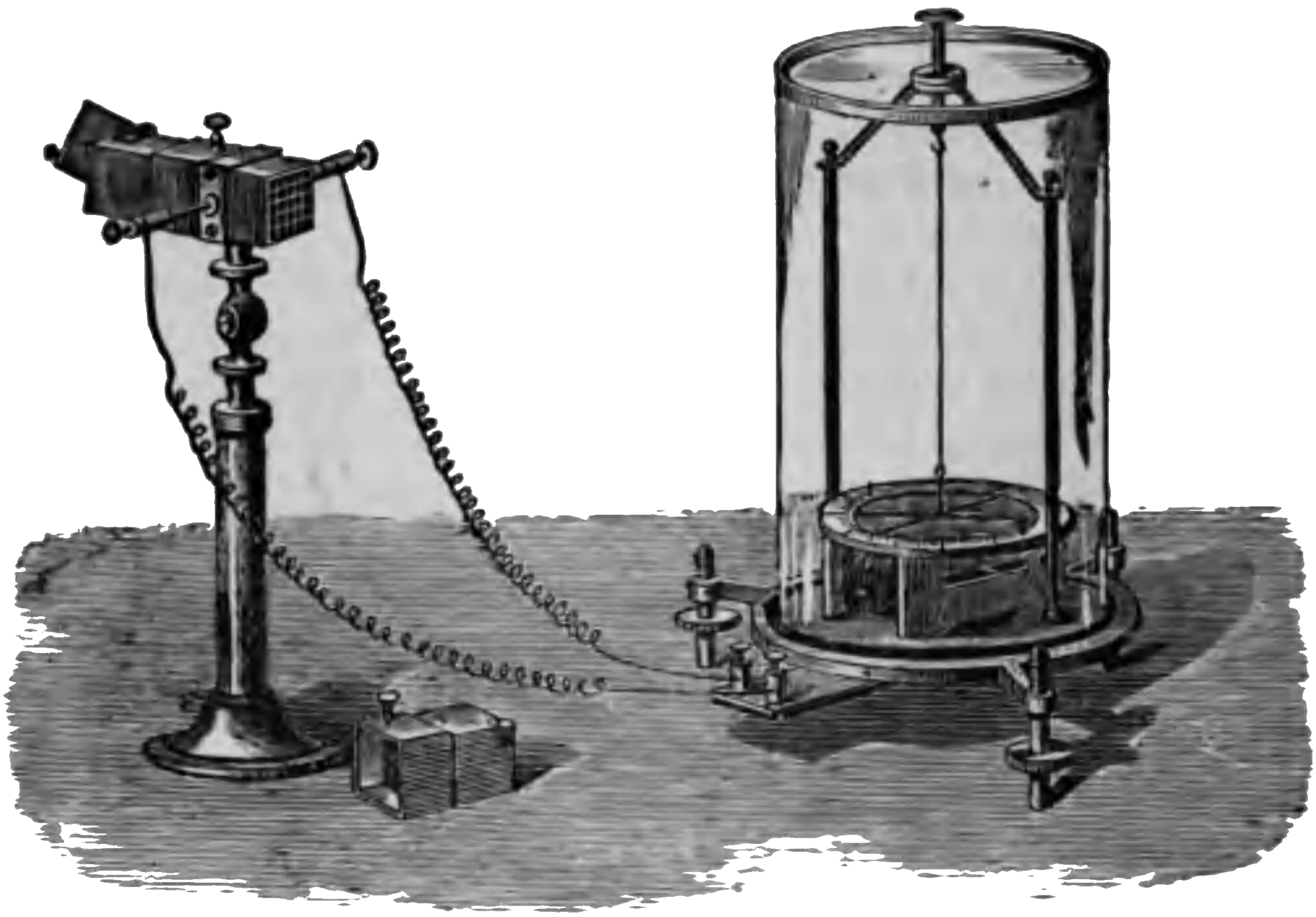


Fig. 225.

poles of a magnet (like the coil in Fig. 126) has its circuit closed at its lower end by a piece of antimony and a piece of bismuth (or alloys of these metals) soldered to a minute disk of copper foil. A rise of temperature of the copper foil even so small as one millionth of a degree will generate a current in the loop and give a deflexion over one division of the scale. With an instrument of this kind the radiant heat of a candle can be detected at a distance of two miles.

CHAPTER VIII

HEAT, POWER, AND LIGHT, FROM ELECTRIC CURRENTS

LESSON XXXVI. — *Heating Effects of Currents*

426. Heat and Resistance. — A current may do work of various kinds, chemical, magnetic, mechanical, and thermal. In every case where a current does work that work is done by the expenditure of part of the energy of the current. We have seen that, by the law of Ohm, the current produced by a given battery is diminished in strength by anything that increases the external resistance. But the current may be diminished, in certain cases, by another cause, namely, the setting up of an opposing electromotive-force at some point of the circuit. Thus, in passing a current through an electrolytic cell (Art. 237) there is a diminution due to the opposing electromotive-force ("polarization") which is generated while the chemical work is being done. So, again, when a current is used to drive an electric motor (Art. 443), the rotation of the motor will itself generate a back E.M.F., which will diminish the current. Whatever current is, however, not expended in this way in external work is *frittered down into heat*, either in the battery or in some part of the circuit, or in both. Suppose a quantity of electricity to be set flowing round a closed circuit. If there were no resistance to stop it it would circulate for ever; just as a waggon set rolling along a

circular railway should go round for ever if it were not stopped by friction. When matter in motion is stopped by friction the energy of its motion is frittered down by the friction into heat. When electricity in motion is stopped by resistance the energy of its flow is frittered down by the resistance into heat. Heat, in fact, appears wherever the circuit offers a resistance to the current. If the terminals of a battery be joined by a short thick wire of small resistance, most of the heat will be developed in the battery and so wasted; whereas, if a thin wire of relatively considerable resistance be interposed in the outer circuit, it will grow hot, while the battery itself will remain comparatively cool.

427. Laws of Development of Heat: Joule's Law.— To investigate the development of heat by a current, Joule and Lenz used instruments on the principle shown in Fig. 226. A thin wire joined to two stout conductors is enclosed within a glass vessel containing alcohol, into which also a thermometer dips. The resistance of the wire being known, its relation to the other resistances can be calculated. Joule found that the *number of units of heat developed in a conductor* is proportional —

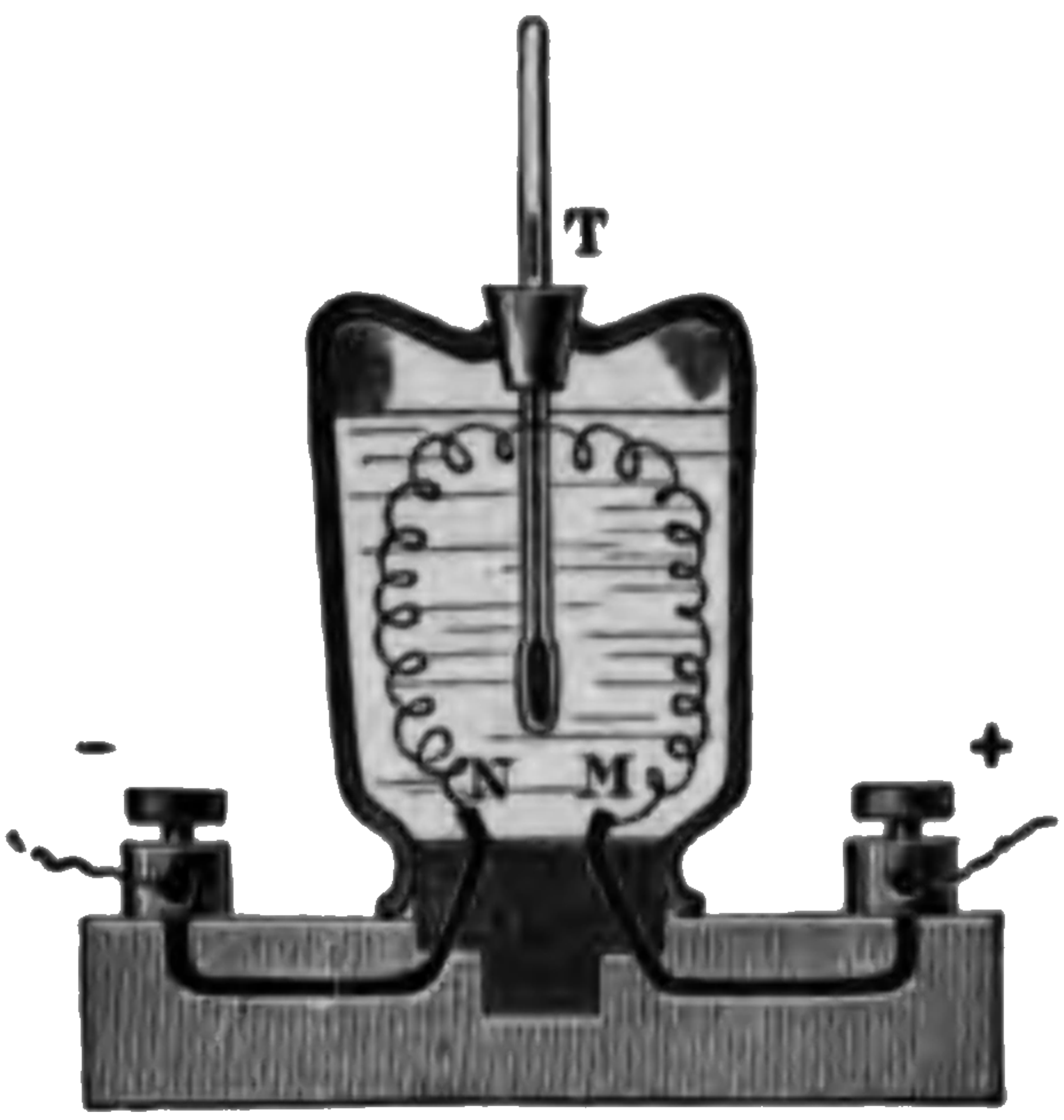


Fig. 226.

(i.) to its resistance;

(ii.) to the square of the strength of the current; and

(iii.) to the time that the current lasts.

The equation expressing these relations is known as Joule's Law, and is —

$$U = C^2Rt \times 0{\cdot}24,$$

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the same instrument, the solution of the same amount of zinc was observed to be accompanied by the evolution of 18,674 calories (*i.e.* an amount almost identical with that observed before), and this amount was the same whether the evolution took place in the battery-cell when the circuit was closed with a short thick wire, or whether it took place in a long thin wire placed in the external circuit. He then arranged 5 Smee's cells in series, in cavities of the calorimeter, and sent their current round a small electric motor. The amount of heat evolved during the solution of 33 grammes of zinc was then observed in three cases: (i.) when the motor was at rest; (ii.) when the motor was running round and doing no work beyond overcoming the friction of its pivots; (iii.) when the motor was employed in doing 13,124,000 gramme-centimetres ($= 12{,}874 \times 10^6$ *ergs*) of work, by raising a weight by a cord running over a pulley. The amounts of heat evolved in the circuit in the three cases were respectively, 18,667, 18,657, and 18,374 calories. In the last case the work done accounts for the diminution in the heat wasted in the circuit. If we add the heat-equivalent of the work done to the heat evolved in the latter case, we ought to get the same value as before. Dividing the $12{,}874 \times 10^6$ *ergs* of work by Joule's equivalent (42×10^6), we get as the heat-equivalent of the work done 306 calories. Now $18{,}374 + 306 = 18{,}680$, a quantity which is almost identical with that of the first observation, and quite within the limits of unavoidable experimental error.

429. Rise of Temperature.—The elevation of temperature in a resisting wire depends on the *nature* of the resistance. A very short length of a very thin wire may resist just as much as a long length of stout wire. Each will cause the same number of units of heat to be evolved, but in the former case, as the heat is spent in warming a short thin wire of small mass, it will get very hot, whereas in the latter case it will perhaps only warm to an imperceptible degree the mass of the long thick wire, which, moreover, has a larger surface to get rid of its heat. If the wire weigh w grammes, and have a specific capacity for heat s, then $U = sw\theta$, where θ is the rise of temperature in degrees (Centigrade). Hence if none of the heat were radiated away

$$\theta = 0{\cdot}24 \times \frac{C^2Rt}{sw}.$$

Since the resistance of metals increases as they rise in temperature, a thin wire heated by the current will resist more, and grow hotter and hotter until its rate of loss of heat by conduction and radiation into the surrounding air equals the rate at which heat is supplied by the current.

The following pretty experiment illustrates the laws of heating. The current from a few cells is sent through a chain made of alternate links of silver and platinum wires. The platinum links glow red-hot while the silver links remain comparatively cool. The explanation is that the specific resistance of platinum is about six times that of silver, and its capacity for heat about half as great; hence the rise of temperature in wires of equal thickness traversed by the same current is roughly twelve times as great for platinum as for silver.

Thin wires heat much more rapidly than thick, *the rise of temperature in different parts of the same wire* (carrying the same current) *would be*, for different thicknesses, *inversely proportional to the fourth power of the diameters* if they had equal surfaces for radiation.

Thus, suppose a wire at any point to become reduced to *half* its diameter, the cross-section will have an area ¼ as great as in the thicker part. The resistance here will be 4 times as great, and the number of heat units developed will be 4 times as great as in an equal length of the thicker wire. But 4 times the amount of heat spent on ¼ the amount of metal would warm it to a degree 16 times as great: and the thin wire has only half as much surface for getting rid of heat. But the hotter a body becomes the more freely does it radiate heat to things around it. For wires of given material, the current needed to raise them to an equal temperature varies as the square root of the cube of the diameter. This law applies to the sizes of wires used as *safety fuses* in electric lighting. These are pieces of tin wire interposed in the circuit to melt if by any chance the current becomes abnormally strong.

430. Cardew's Voltmeter. — The current flowing through a long thin wire of platinum when it is made to connect two points on a circuit will measure the potential difference between these two points. Owing to its becoming warmed it will expand, and its expansion may be made to move a hand over a dial graduated to read volts (Fig. 227).

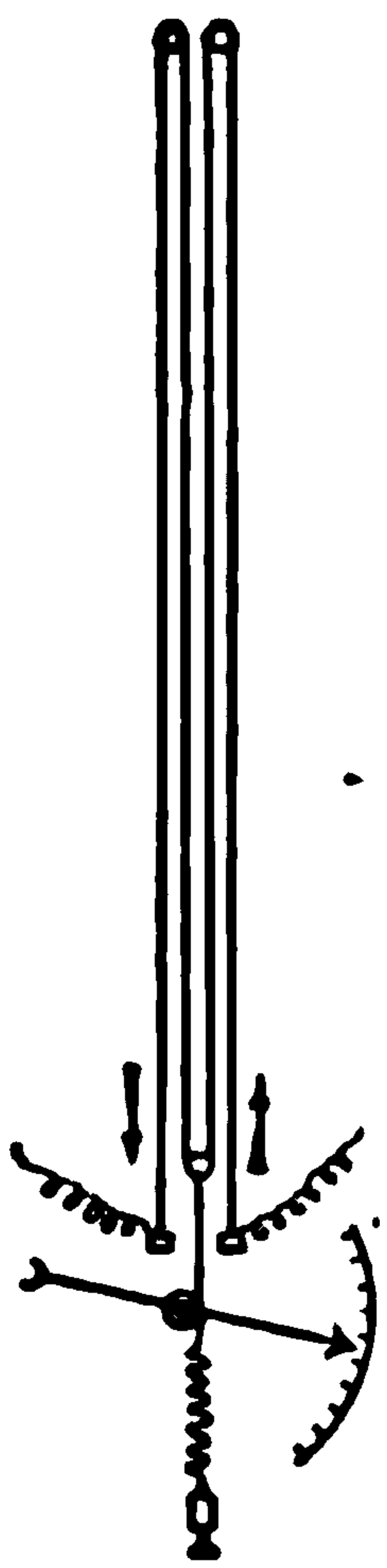


Fig. 227.

431. Electric Cautery.—For surgical purposes a thin platinum wire, heated red-hot by a current, is sometimes used instead of a knife, as, for example, in the operation of amputating the tongue for cancer. Platinum is chosen on account of its infusibility, but even platinum wires are fused by the current if too strong. Carbon alone, of conductors, resists fusion.

432. Blasting by Electricity. — In consequence of these heating effects, electricity can be applied in blasting and mining to ignite the charges. Stout conducting wires are carried from an appropriate battery at a distance to a special *fuze*, in which a very thin platinum wire is joined in the circuit. This wire gets hot when the current flows, and being laid amidst an easily combustible substance to serve as a priming, ignites this and sets fire to the charge of gunpowder. Torpedoes can thus be exploded beneath the water, and at any desired distance from the battery.

433. Electric Welding. — If two wires or rods of metal are held together with sufficient force while a very large current is passed through them, much heat is developed at the junction, so that they soften and become welded together. The processes of *electric welding* have been perfected by Elihu Thomson, who has utilized for this purpose alternate-current transformers (Art. 480) to

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(Art. 263) that the work done is equal to QV. If this is occurring in a battery or dynamo, QV represents electrically the work (chemical or mechanical) done on the system, or the energy received (electrically) by the system. Now, suppose this operation to have occupied time t, the *rate* at which the energy is being imparted to the circuit will be QV/t. But (Art. 162) $Q/t = C$. Hence the *power* given to the circuit is equal to CV.

This justifies the statement that *the power of an electric current* to perform useful work, whether in lighting, heating, or producing mechanical actions, *is proportional both to the strength of the current, and to the electromotive-force which drives it.* In other words, *power* is proportional to both amperes and volts jointly. Similarly the power of a steam engine is proportional not only to the quantity of steam it uses, but also to the pressure at which the steam is supplied. The electric unit of power will then be the power of a current of 1 ampere driven by an electric pressure of 1 volt. This unit is known as 1 volt-ampere, or 1 *watt*.

Since 1 volt = 10^8 absolute units of E.M.F. (Art. 354) and 1 ampere = 10^{-1} absolute units of current (Art. 354), it follows that 1 watt = 10^7 absolute units of power (*i.e.* 10^7 ergs per second). But 1 horse-power = 746×10^7 ergs per second (see above). Hence 1 H.P. = 746 watts.

One thousand watts is called 1 *kilowatt*. The kilowatt is therefore approximately $1\frac{1}{3}$ H.P.

To find the number of watts of power supplied by any dynamo or battery, multiply the number of amperes of current by the number of volts at which the current is driven. The same rule serves to calculate the power electrically delivered to any motor, lamp, accumulator, or other means of spending electric energy.

$$\text{Horse-power} = C \times V \div 746.$$

Example.—If a current of 20 *amperes* is supplied to a big arc-lamp at a pressure of 56 *volts*, find the amount of power absorbed therein. *Ans.* 1120 *watts* or $1\frac{1}{2}$ H.P.

436. Intake and Output of Power.—At any generator battery, dynamo, or thermopile, power is taken in to the electric circuit. At any motor or lamp, or at any part in the circuit where chemical work (electroplating, decomposing gases, or charging accumulators) is being done or at any place where heat is being evolved, power is being given out by the electric circuit. At every place where energy is coming in to the circuit there will be an electromotive-force *in the same direction as the current*, and helping to drive it. At every part where energy is being given out by the circuit there will be an electromotive-force *in a direction opposed* to the current.* The word *output*,† as applied to dynamos, etc., means the number of watts or kilowatts which the machine supplies or can supply. For example, a dynamo capable of supplying 300 amperes "at" 100 volts (meaning with an available E.M.F. of 100 volts) is said to have an output of 30 kilowatts.

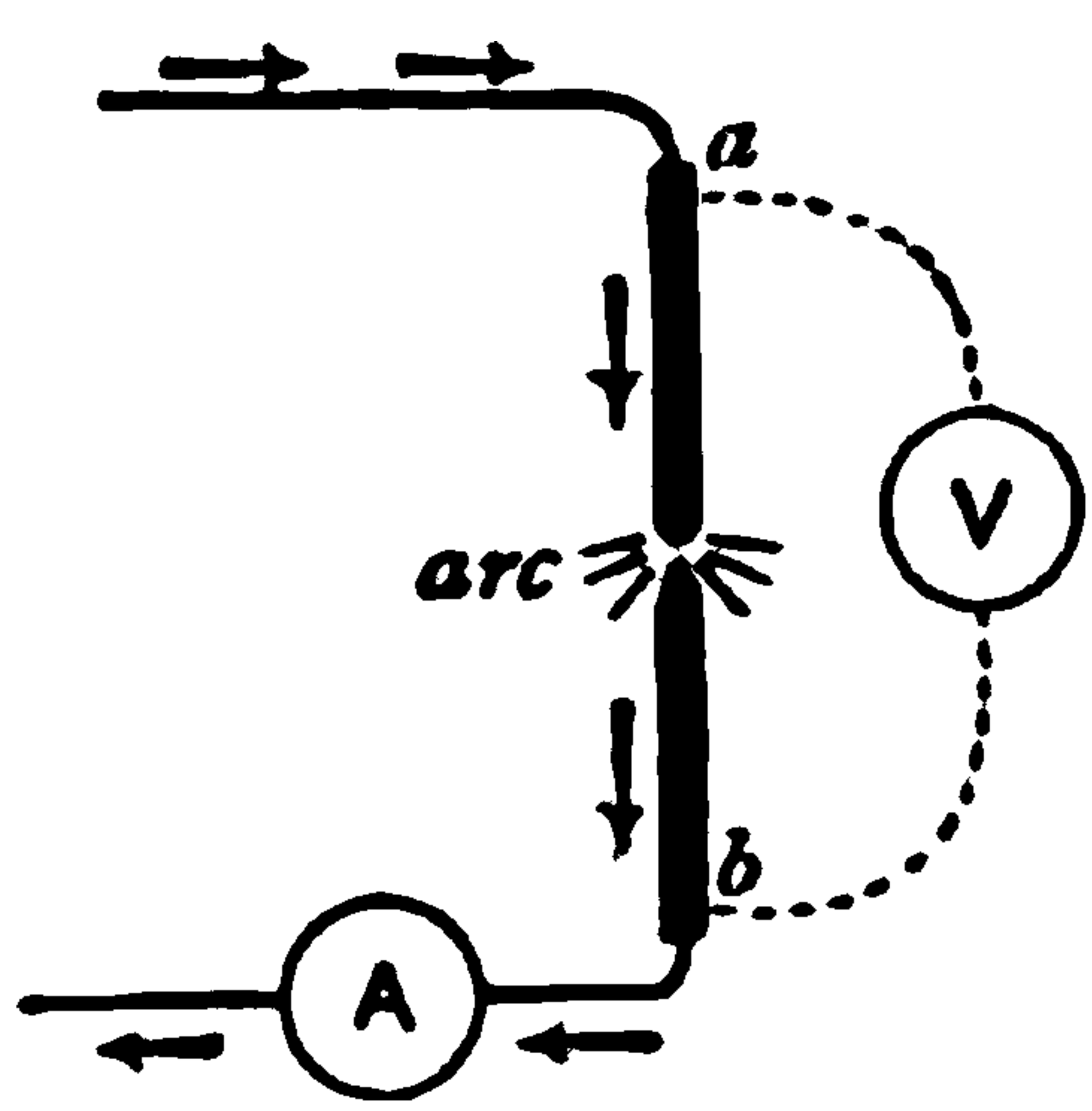


Fig. 228.

437. Power-Measurement.—To measure the power given electrically to any part *ab* of a circuit by an unvarying current, it suffices to measure the current with an *ampere-meter* (Art. 221), and the potentials across the part with a *voltmeter* (Arts. 220, 290), the latter being of course con-

* Consider the mechanical analogue of transmission of power from one pulley to another pulley by a belt. The effort in the driving pulley is in the same direction as the motion of the belt. The effort in the driven pulley is opposed in direction to the motion. (See also Art. 248.)

This fundamental principle accounts for the back-electromotive-forces observed in motors, and in accumulators while being charged. Because of it we know (Art. 166) that the seat of the main electromotive-force in a voltaic cell is at the surface of the zinc, and that (Art. 422) bismuth is thermo-electrically positive to antimony.

† The word *output*, as applied to central station work, is sometimes used in sense of total outflow of amperes irrespective of voltage.

nected as a shunt as in Fig. 228. The product of volts and amperes gives the watts. Or a *wattmeter* may be used as below.

438. Wattmeters.—The product of amperes and volts may be measured directly by means of a *wattmeter*. This name is given to a variety of electrodynamometer (Art. 394) in which the fixed and movable coils constitute two separate circuits, one being a thick wire of low resistance to carry the *amperes*, the other being, or including, a thin wire of high resistance (as in voltmeters) to receive a current proportional to the *volts*. The latter circuit is to be connected as a shunt to the part *ab* of the circuit in which the supplied power is to be measured. In Fig. 229, as in Fig. 228, the part *ab* is an arc-lamp. The auxiliary resistance *r* is introduced into the thin-wire circuit of the instrument, the whole current flowing through the thick-wire circuit.

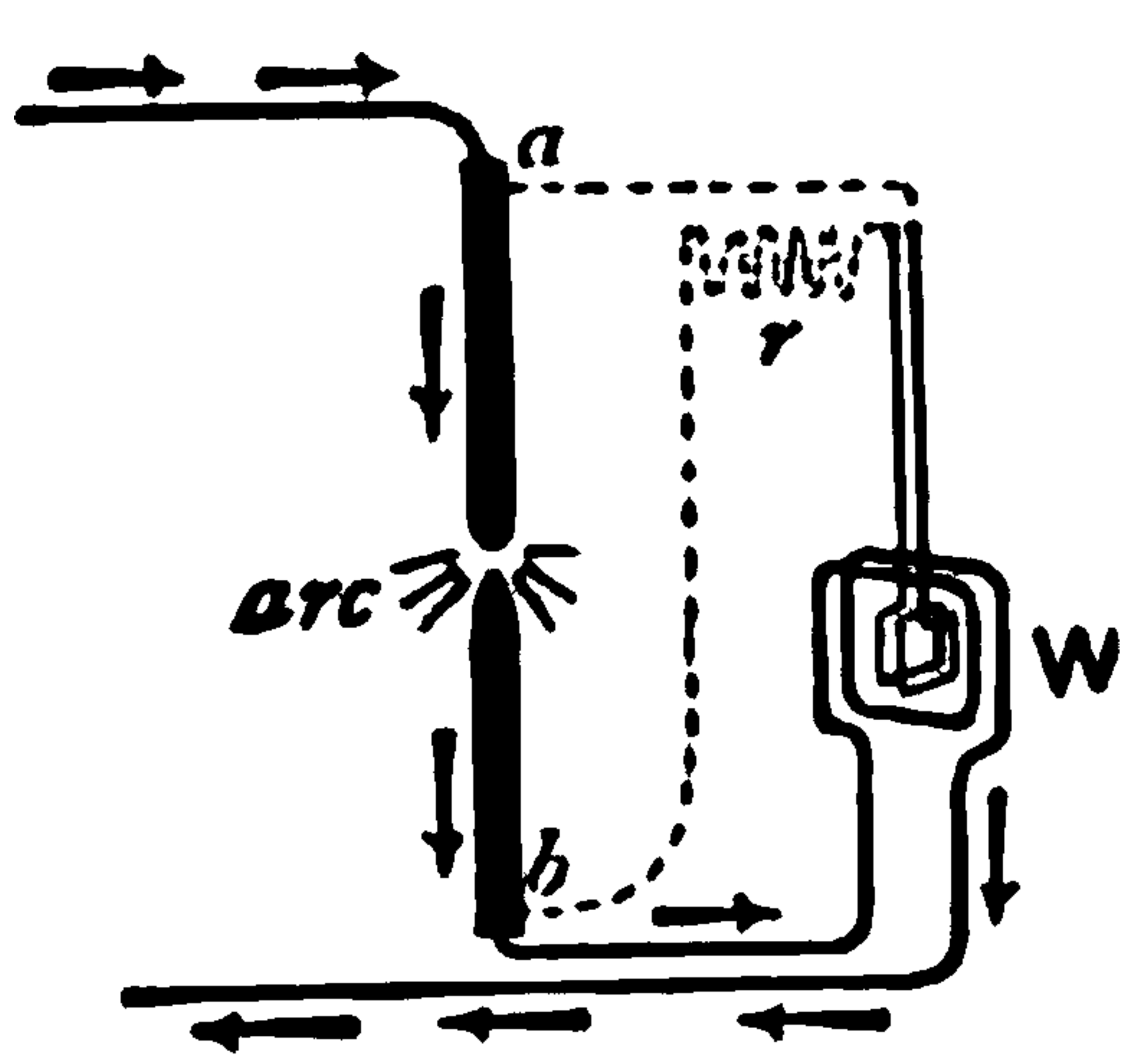


Fig. 229.

Wattmeters are made both on the pattern of Siemens's dynamometer (Art. 395) and on that of Kelvin's balances (Art. 396).

When power-measurements have to be made on alternate-current circuits, separate instruments must not be used, as in Art. 437, to measure volts and amperes. For, owing to the differences of phase (Art. 472) between voltage and current, the *apparent watts*, got by multiplying the separate readings, will be in excess of the true watts as measured by a wattmeter.

439. Power wasted in Heating.—If a current C is driven through a resistance R, the volts needed will (by Ohm's law) be

$$V = CR.$$

The power CV so expended will merely heat the resistance.

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480) to transform to low pressure at the consumers' houses.

Example.—The City of London Electric Lighting Company generates alternate currents at a little over 2000 volts at its power-house on the south side of the Thames, and sends these currents through the feeders to sub-stations in the city, where they are transformed down to currents twenty times as large at a pressure of 100 volts; at which low pressure they supply the network of mains and house branches, which are laid in conduits under the streets.

Since the power of a current depends on the voltage at which it is supplied, the *unit of supply* recognized in law is based on the unit of power, the *watt* (Art. 435), and is defined as 1000 watts supplied for one hour (*i.e.* 1 kilowatt-hour) or its equivalent. The maximum price which the English Board of Trade permits the supply company to charge the consumer for 1 unit is eightpence.

441. Conditions of Electric Supply.—Electric energy is almost always supplied under one of two standard conditions, either—

(*a*) at *Constant Voltage*, or
(*b*) with *Constant Current*.

In the former case the circuit is branched, and the current is supplied (usually at 100 volts) to all the lamps or motors *in parallel* (Art. 409), each lamp, etc., being independent of all others; and the current varying precisely in proportion to the demand.

In the latter case, seldom used except for strings of arc-lamps, the circuit is undivided, and the current (usually 10 amperes) flows through all the lamps *in series* (Art. 168). If lamps are turned out (by short-circuiting them) the voltage must be reduced to keep the current constant.

442. Supply Meters.—Meters for measuring the supply to the houses of consumers are of several kinds.

(*a*) *Chemical Meters.*—The current or a known fraction

of it is passed through an electrolytic cell, there to deposit copper (Edison's method) or dissolve zinc (Jehl's improved Edison). The amount of chemical action is proportional to the ampere-hours.

(*b*) *Integrating Meters.* — A uniformly-going clock drives a counting apparatus through an intermediate gear operated by the current (or by the watts), such intermediate gear being such that when current is small counting is small, when current large counting is large. An integrating disk-and-roller, or an integrating cam, is a usual mechanism, its operation being controlled by the motion of an ampere-meter or wattmeter.

(*c*) *Motor Meters.* — If the current passes through the armature of a small motor (Art. 443) having a constant field, having its speed controlled purely by fluid friction (by a fan) or by eddy-current friction (in a copper conductor revolving between magnet poles, Art. 457), its speed will at every instant be proportional to the current. Hence such a motor attached to a suitable counting-train of wheels will serve as a meter, the total number of revolutions being proportional to the ampere-hours. In Perry's meter (1893) the revolving part is a copper bell immersed in mercury, revolving around a central magnet pole (as the wire does in Fig. 201), and surrounded by an external S pole with ribbed projections to promote eddy-currents. In Schallenberger's meter for alternate currents the motor drives a fan. In Elihu Thomson's meter, which records the watt-hours, the revolving armature is of fine wire and high resistance, connected as shunt, while the fixed coils that serve as field-magnet take the whole current supplied. So the torque is proportional to the watts; while a copper disk revolving between magnet poles, by its drag keeps the speed proportional to the torque.

(*d*) *Retarded Clocks.*—Current may be made to act upon the rate of a clock, by flowing in a coil under the pendulum bob if the latter is a magnet. Any force added thus to gravity or subtracted from it will cause the clock to gain or lose. Ayrton and Perry proposed to measure the supply by the total time gained or lost by a clock. In Aron's meter, of which this is the principle, there is a double clock with two pendulums, only one of which is acted on by the current. A train of counting wheels is geared to record the difference between the two.

Lesson XXXVIII.—*Electric Motors (Electromagnetic Engines)*

443. Electric Motors.—Electromagnetic engines, or *motors*, are machines in which the motive power is derived from electric currents by means of their electromagnetic action. In 1821 Faraday showed a simple case (Art. 393) of rotation produced between a magnet and a current of electricity. Barlow produced rotation in a star-wheel, and Sturgeon in a copper disk, when traversed radially by a current while placed between the poles of a horse-shoe magnet. In 1831 Henry, and in 1833 Ritchie, constructed small engines producing rotation by electromagnetic means. Fig. 230 shows a modification of Ritchie's motor. An electromagnet DC is poised upon a vertical axis between the poles of a fixed magnet (or electromagnet) SN. A current, generated by a suitable battery, is carried by wires which terminate in two mercury-cups, A, B, into which dip the ends of the coil of the movable electromagnet CD. When a current traverses the coil of CD it turns so as to set itself in the line between the poles NS, but as it swings round, the wires that dip into the mercury-cups pass from one cup

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Jacobi appears to have been the first to recognize, about 1850, that the action of the electric motor is the simple converse of that of the dynamo or generator. Every magneto-electric generator or dynamo, such as is used in electric lighting, can also work as a motor, giving out mechanical power when supplied with electric currents from some other source. Indeed the dynamos designed as generators make far more efficient motors than any of the older sorts of electromagnetic engines, which were little more than toys.

In 1882 an iron screw-boat capable of carrying 12 persons, and driven by two such motors, with a power of about 3 horse-power, the current being furnished by 45 accumulators, was worked upon the Thames at a speed of 8 miles per hour. There is now a whole flotilla of electric launches on the Thames.

444. Modern Electric Motors. — These are of two kinds: (1) those for use with continuous currents; (2) those for use with alternate currents. The former are constructed precisely on the plan of continuous current dynamos (Art. 462) having fixed *field magnets* and rotating *armature*. The armature is dragged round by the mutual action of the currents flowing in the copper conductors and the magnetic field in which the conductors lie. As explained in Art. 340, the force acting laterally on the conductors is proportional to the product of current and field. Hence if very powerful field-magnets are employed, a great torque (or turning moment) can be produced without requiring too great a current to be sent into the armature. The two factors of mechanical rotatory power are *torque* (= angular force) and angular *speed*. If the field of the motor is maintained constant the torque is proportional to the current and the speed is proportional to the volts. If E is the electromotive-force generated (in direction opposing the current, see Art. 436) in the revolving armature, and C the current supplied to it, the electrical and mechanical expressions for the power

(watts) imparted to the armature are

$$CE = anT,$$

where n is revolutions per second, T the torque, and a a coefficient depending on the units chosen.

If the armature current is supplied from mains at constant voltage, strengthening the magnetic field has the effect of slowing speed, for equal power; and weakening the field quickens the speed. Alternate-current motors are described in Arts. 484 to 486.

445. Efficiency of Motors. — If an ampere-meter be included in the circuit with a battery and a motor, it is found that the current is *weaker* when the motor is working than when the motor is standing still, and that the faster the motor runs the weaker does the current become. This is due to the E.M.F. generated in the revolving armature of the motor, which necessarily (Art. 436) opposes the current. If the motor only exerts a small back electromotive-force it cannot utilize much of the power of the current. If V be the volts at which the current is supplied, and E the counter-electromotive-force generated by the motor, and C the current, then VC = gross power supplied, EC = nett power utilized; and dividing the latter by former we get, as the electrical *efficiency* of the motor, the ratio $\frac{E}{V}$.

Example. — Suppose V = 100 volts and E = 90 volts, the efficiency will be 90 per cent.

To make the efficiency as high as possible the motor should be so arranged (either by strengthening its magnetic field, or by letting it run faster) that E is very nearly equal to V. In that case the motor will utilize nearly all the energy that flows to it. But since, by Ohm's law, the current is $= (V - E)/r$, where r is the internal resistance of the motor, it follows that when E becomes nearly equal to V the current will be reduced to

a small fraction what it would be if the motor were at rest. The diagram (Fig. 231) makes the matter plainer. Let the line OV represent by its length the volts of supply V, and let OE represent the volts generated in the armature, proportional to speed and to field. On OV describe the square OVWX, and draw the diagonal and the lines EH, KL. Then the area EVWH is proportional to the gross power, being $V(V-E)$, and area GLXH is proportional to the nett power, being $E(V-E)$. These two areas become more nearly equal, though both become small, when E is increased to be nearly equal to V. The area GLXH, the nett output of the motor, is a maximum when $E = \frac{1}{2}V$; but then the efficiency would be only 50 per cent.

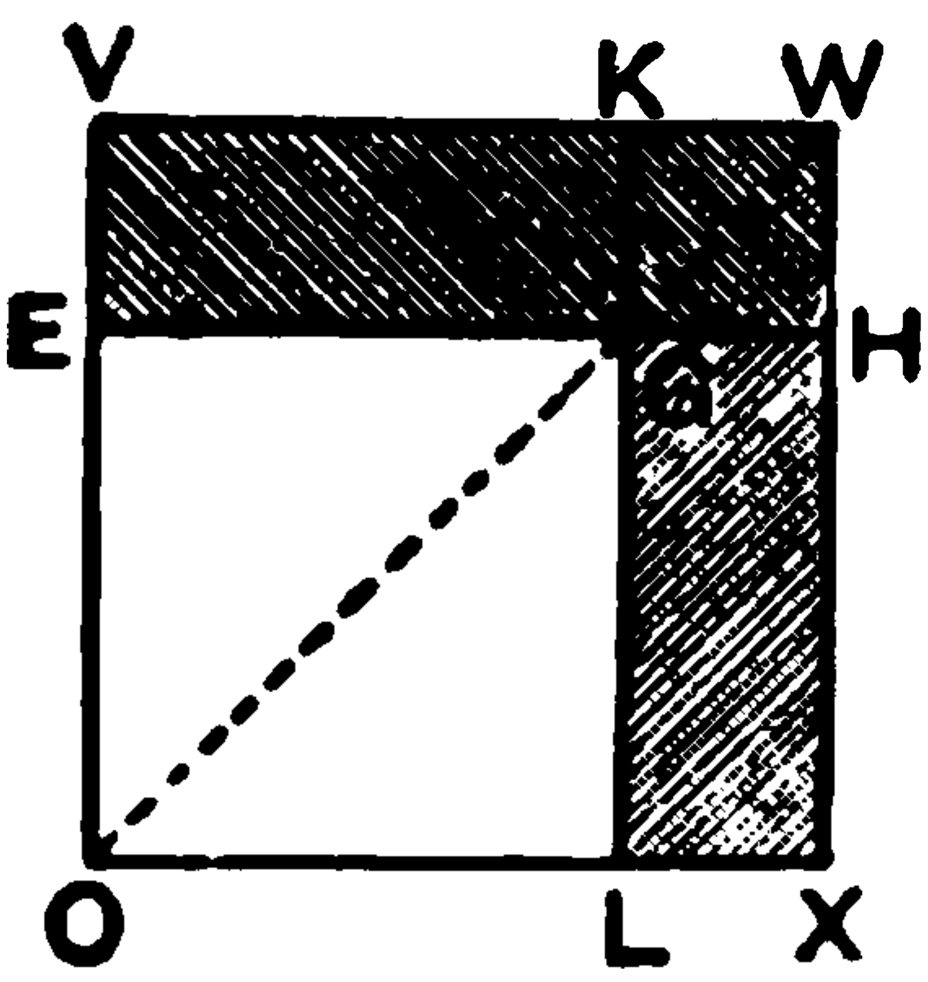


Fig. 231.

The fact that when E is small the current is enormous is of great advantage in the starting of motors; for at starting the great rush of current (which would destroy them if it lasted) produces a great torque, and the motor soon gets up speed and so cuts down the current to the working amount.

446. Electric Locomotion. — Motors placed on cars or on separate locomotives can propel them singly or in trains provided the requisite power is supplied. This may be done in several ways: —

(*a*) A battery of charged accumulators is carried on the car.

(*b*) Current is furnished from a power-house, at some convenient point, to the rails on which the cars run, and which act as outgoing and return conductors, and are insulated. The cars (which have insulated wheels) pick up their currents from the rails.

(*c*) Current is furnished from a power-house, to a third

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to the prohibitive price of copper for carrying large currents without overheating. The watts wasted in a line of resistance R are (Art. 439) $= C^2R$. The gross watts utilized are (Art. 435) $= CV_M$, where V_M is the volts at the motor end. Hence the power that must be poured in to the sending end of the line $C^2R + CV_M$ watts. Now it will be obvious that one may keep the C^2R loss constant and yet increase the power that is transmitted by increas-

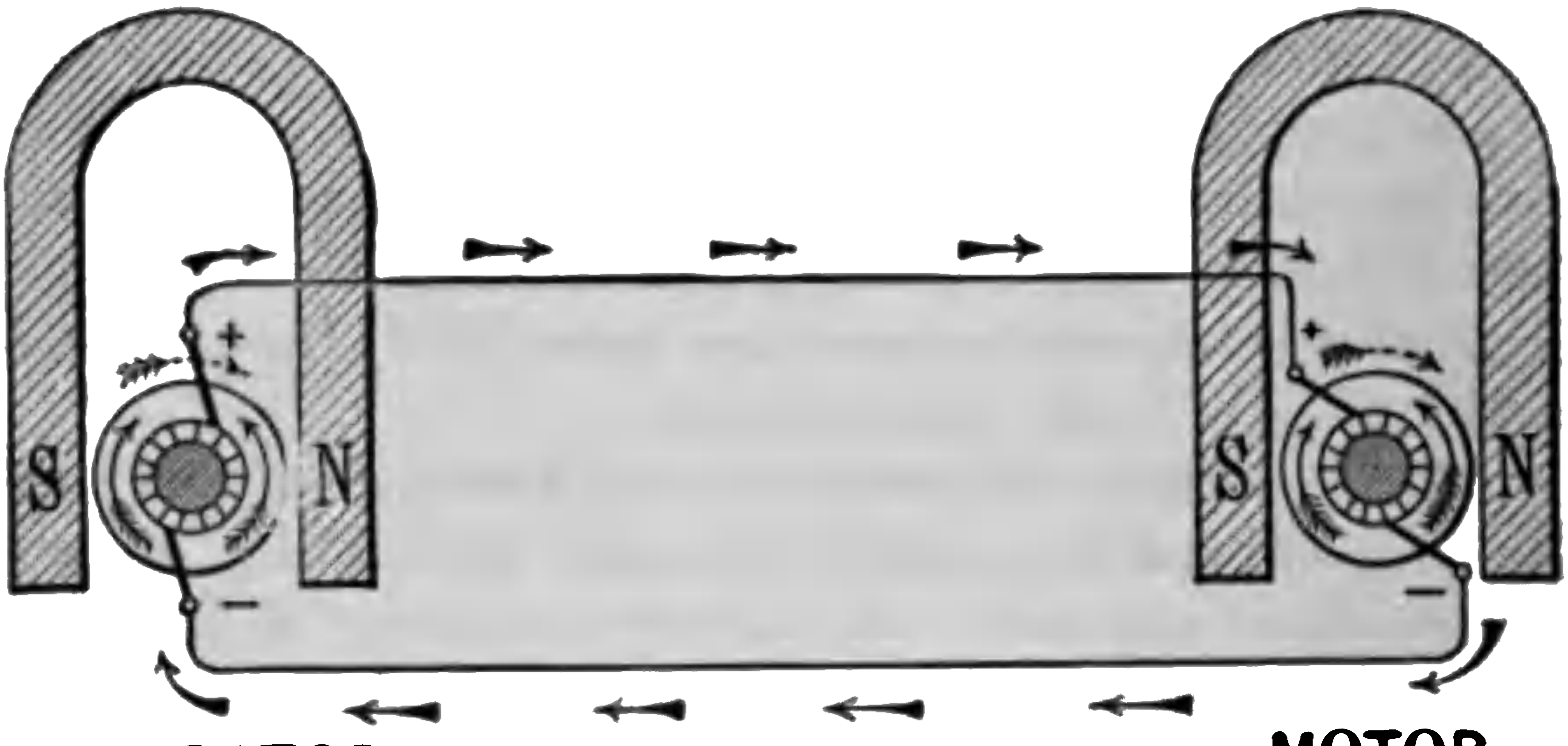


Fig. 282.

ing V_M the voltage at the motor — using in fact a high-voltage motor, and of course a high-voltage generator to correspond. To put the matter in another way. Let V_G be the volts at the generator end of the line, $(V_G - V_M)R$ will be $= C$. Now we may keep C constant (and therefore the C^2R loss constant) and yet increase the voltages, provided $V_G - V_M$ remains as before.

Example.—Suppose a line of copper-wire 20 miles long has resistance of 100 ohms. A current of 6 amperes in it will waste 3600 watts or nearly 5 horse-power. To send 6 amperes through 100 ohms requires a difference of potentials of 600 volts. Suppose $V_G = 1000$ and $V_M = 400$, $V_G - V_M = 600$. The watts sent in are $CV_G = 6000$, and the watts delivered are $CV_M = 2400$. Of 8 horse-power put in only about $3\frac{1}{4}$ are delivered, the

efficiency being $V_M/V_G = 40$ per cent. Now suppose V_G increased to 2000 volts, and V_M to 1400. $V_G - V_M =$ 600, as before. $C = 6$ amperes, as before. C^2R loss is 3600 watts, as before. But watts sent in are now 12,000 (over 16 H.P.), and the watts delivered are 8400 (11¼ H.P.). Whilst the efficiency is now 70 per cent.

It is therefore clear that *high voltage* is the secret of success in the electrical transmission of energy, whether for lighting or power, to long distances. In the transmission of energy from the Falls of Tivoli to light the city of Rome sixteen miles away, a pressure of 5000 volts is successfully used. In the scheme for utilizing the power of Niagara Falls, now on the way, a voltage of 30,000 is proposed.

Lesson XXXIX. — *Electric Light*

448. The Electric Arc. — If two pointed pieces of carbon are joined by wires to the terminals of a powerful voltaic battery or other generator of electric currents, and are brought into contact for a moment and then drawn apart to a short distance, a kind of electric flame called the arc or "voltaic" arc is produced between the points of carbon, and a brilliant light is emitted by the white hot points of the carbon electrodes. This phenomenon was first noticed by Humphry Davy in 1800, and its explanation appears to be the following: — Before contact the difference of potential between the points is insufficient to permit a spark to leap across even $\frac{1}{10000}$ of an inch of air-space, but when the carbons are made to touch, a current is established. On separating the carbons the spark at parting volatilizes a small quantity of carbon between the points. Carbon vapour being a partial conductor allows the current to continue to flow across the gap, provided it be not too wide; but as the carbon vapour has a very high resistance it becomes intensely heated by the passage of the current, and the carbon points

also grow hot. Since, however, solid matter is a better radiator than gaseous matter, the carbon points emit far more light than the arc itself, though they are not so hot. The temperature of the arc is simply determined by the temperature at which carbon volatilizes; about 3500° C. according to Violle. In the arc the most infusible substances, such as flint and diamond, melt; and metals such as gold and platinum are even vaporized readily in its intense heat. When the arc is produced in the air the carbons slowly burn away by oxidization. It is observed, also, that particles of carbon are volatilized off and torn away from the + electrode, which becomes hollowed out to a cup-shape, or *crater*, and if the gap between the carbons is small some of these particles are deposited on the − electrode, which assumes a pointed form, as shown in Fig. 233.



Fig. 233.

The resistance of the arc may vary, according to circumstances, from 0·2 ohm upwards, according to the length and section of the flame. The arc also exerts an opposing electromotive-force of its own, amounting to about 35 volts when continuous currents are used, and the arc is silent. When it becomes unstable and hisses, the back electromotive-force is much lower. The seat of this back electromotive-force is at the surface of the crater where the work of volatilizing the carbon is being done.

To produce an electric light satisfactorily a minimum electromotive-force of 40 to 50 volts is necessary if continuous currents are used. With alternate currents 30 to 35 volts suffice. The usual current for arc lamps of 1000 to 2000 candle power is from 5 to 10 amperes. With

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pencils to touch, and then separate them to the requisite distance, about 5 millimetres; the mechanism should also "feed" the carbons into the arc as fast as they are consumed, and it should also cause the points to approach or recede automatically in case the arc becomes too long or too short; it should further bring the carbons together for an instant to strike the arc again if by any chance the flame goes out. *Arc Lamps* or "regulators," fulfilling these conditions, have been invented by a number of persons. The earliest was invented in 1847 by W. E. Staite. Arc lamps may be classified as follows:—

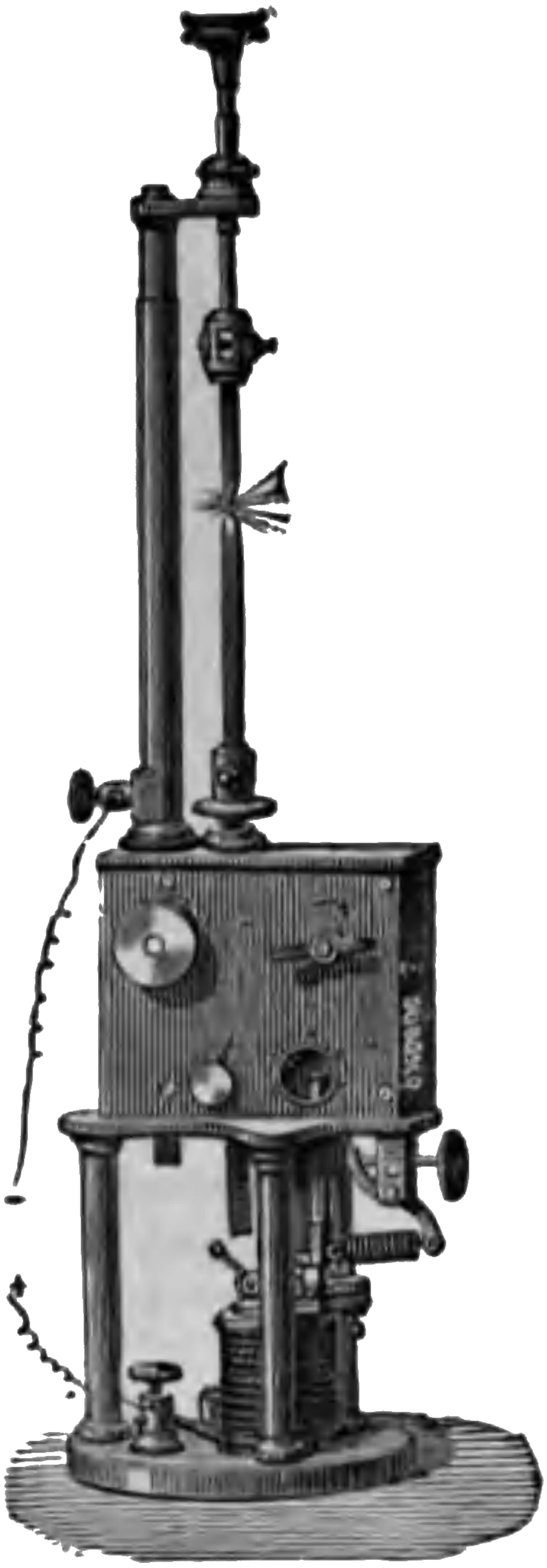


Fig. 234.

(*a*) *Clockwork Lamps.*—Fig. 234 shows the regulator of Foucault as constructed by Duboscq; in this lamp the carbon-holders are propelled by a train of clockwork wheels actuated by a spring. An electromagnet at the base, through which the current runs, attracts an armature and governs the clockwork. If the current is too strong the armature is drawn down, and the clockwork draws the carbons farther apart. If the current is weakened by the increase of the resistance of the arc as the carbons burn away, the armature is drawn upwards by a spring, and a second train of wheels comes into play and moves the carbons nearer together. Clockwork arc

lamps have also been devised in which the weight of the carbon-holders drive the clockwork mechanism. Of this class was Serrin's lamp, which from 1855 to the present time has been largely used for lighthouses, and for the optical lantern.

(*b*) *Brake-wheel Lamps.* — Another mechanism for regulating the rate of feeding the carbon into the arc consists in the addition of a brake-wheel; the brake which stops the wheel being actuated by an electromagnet which allows the wheel to run forward a little when the resistance of the arc increases beyond its normal amount. In Fig. 235 B is the brake-wheel, L the lever which governs it, C an iron core of the coil S inserted in the circuit. When current is switched on, the core is drawn up, causing L to grip B and turn it a little, so parting the carbons and striking the arc.

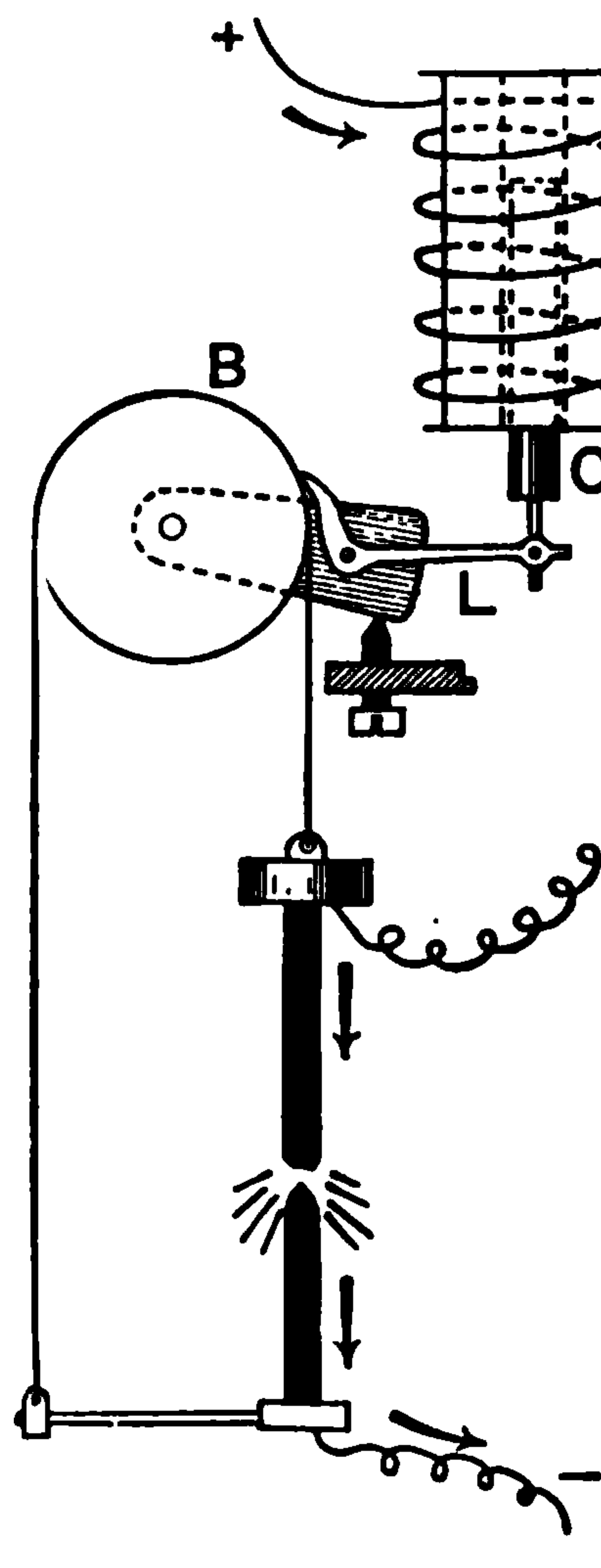


Fig. 235.

(*c*) *Solenoid Lamps.* — In this class of arc lamp one of the carbons is attached to an iron plunger capable of sliding vertically up or down inside a hollow coil or solenoid, which, being traversed by the current, regulates the position of the carbons and the length of the arc. Siemens employed two solenoids acting against one another differentially, one being a main-circuit coil, the other being a fine-wire coil connected as a *shunt* to the arc. The shunt coil acts as a *voltmeter* to watch the arc and feed the carbons forward when the volts rise above the normal, it being set to control the feeding mechanism.

(*d*) *Clutch Lamps.* — A somewhat simpler device is

that of employing a clutch to pick up the upper carbon-holder, the lower carbon remaining fixed. In this kind of lamp the clutch is worked by an electromagnet, through which the main current passes. If the lamp goes out the magnet releases the clutch, and the upper carbon falls by its own weight and touches the lower carbon. Instantly the current starts round the electromagnet, which causes the clutch to grip the carbon-holder, and raise it to the requisite distance. Should the arc grow too long, the lessening attraction on the clutch automatically permits the carbon-holder to advance a little.

(*e*) *Motor Lamps.*—Sometimes little electric motors are used to operate the carbons automatically.

450. Grouping of Arc Lamps.—If the condition of supply is constant voltage the arc lamps must be set *in parallel;* if the arc lamps are to be run *in series*, the same current flowing in succession through each of the lamps, then the supply must be of a current of unvarying strength. In this case a shunt circuit is necessary in each lamp.

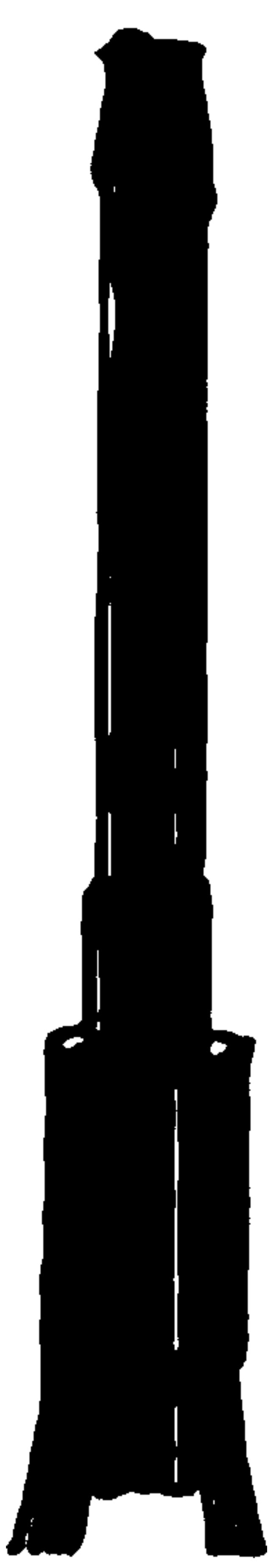


Fig. 236.

451. Electric Candles.—To obviate the expense and complication of such regulators, electric *candles* have been suggested. Fig. 237 depicts *Jablochkoff's candle*, consisting of two parallel pencils of hard carbon separated by a thin layer of plaster of Paris and supported in an upright holder. The arc plays across the summit between the two carbon wicks. In order that both carbons may consume at equal rates, alternating currents must be employed.

452. Incandescent Lamps or Glow-Lamps.—Arc lamps of an illuminating power of less than 100 candles are very unsteady and uneconomical. For small lights it is both simpler and cheaper to employ a thin continuous wire or filament of some infusible conductor, heated to whiteness by passing a current through it. Thin wires of platinum

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ing to size and length of the filament. A modern 16 candle-power lamp for use on a 100-volt circuit will take about 0·6 ampere. That is to say, its resistance when hot will be about 166 ohms (or over 200 ohms when cold), and it will absorb about 60 watts. This is at the rate of less than 4 watts per candle. Used so, it will last on the average over 1000 hours of burning. Lamps are made to give equal light and use less current, by using a thinner and rather shorter filament; but then they do not last so long. The surface disintegrates in time if forced to emit too much light. The power required to operate 12 such 60-watt lamps will be 720 watts, or nearly 1 horse-power.

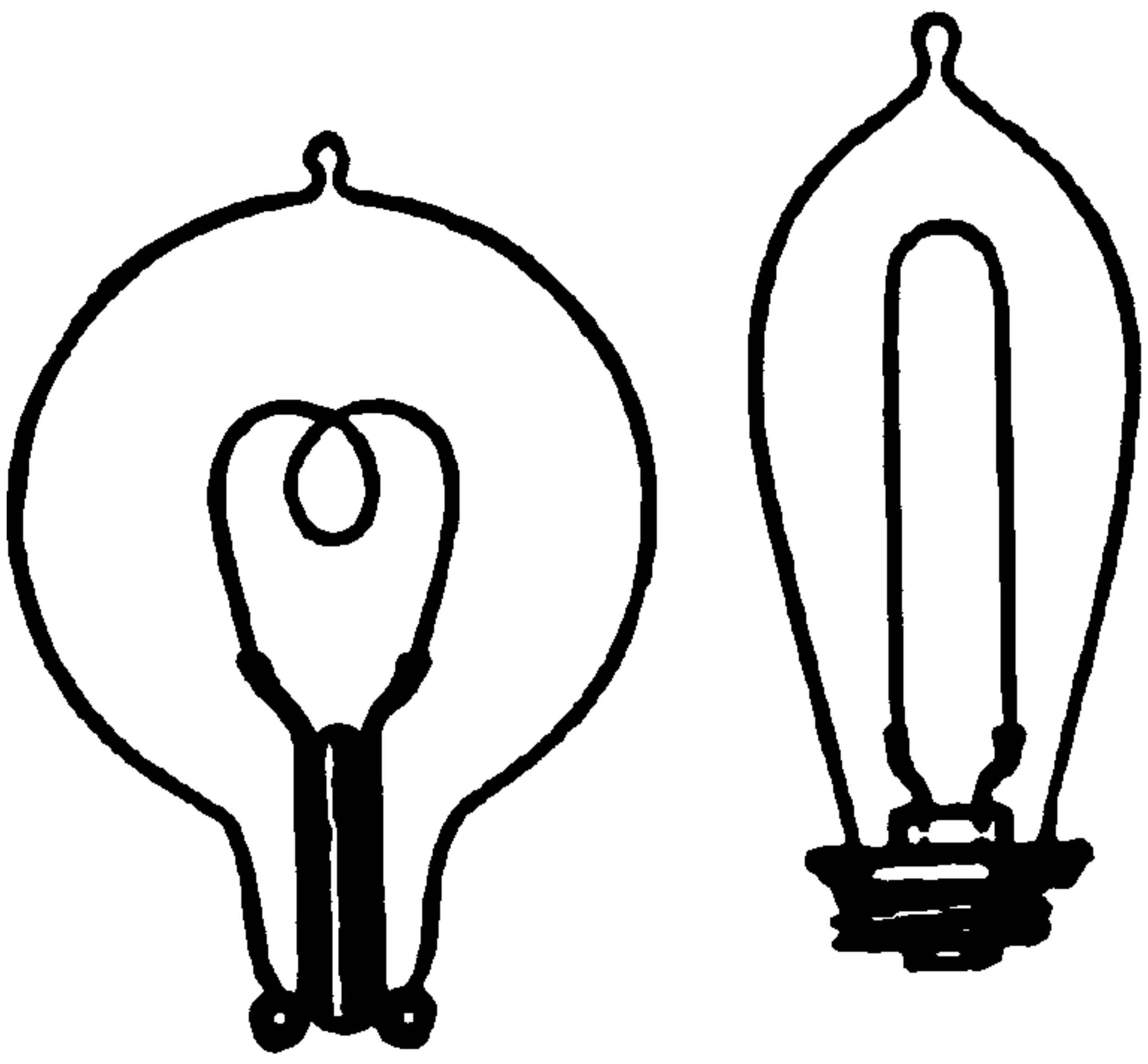


Fig. 237.

The following table gives some data about a 10-candle 50-volt lamp if used at different voltages.

Volts.	Amperes.	Watts.	Candle-power.	Watts per candle.	Probable life (hours).
48	0·77	37	8	4·3	3200
50	0·81	40·5	10	4·05	1500
53	0·87	46·4	14·5	3·2	800
55	0·92	50·6	18·5	2·7	480
58	0·99	57·5	25·5	2·2	250
61	1·06	64·7	35·5	1·8	150

The light increases as about the sixth power of the volts; the energy consumed is only as the second power. But raising the volts a little shortens the life enormously.

For special lamps of larger candle-power, up to 800 or 1000, thin filaments cannot be used. In these flat strips or thick wires of carbon are used; they give out, for equal expenditure of power, much less light than an arc lamp.

453. Grouping of Glow-Lamps. — Glow-lamps are usually grouped *in parallel* (Fig. 238) between mains kept at constant voltage. A common value for the difference of potential between the + and − mains is 100 volts. The current in the mains subdivides and flows through each lamp independently. When any lamp is switched on it does not diminish the current in the others, but by opening an additional path simply causes proportionately more current to flow from the source of supply. The method of grouping *in series* (Art. 168) is seldom used for glow-lamps; each lamp then requires an automatic cut-out to prevent the rest of the row from being extinguished in case one lamp goes out.

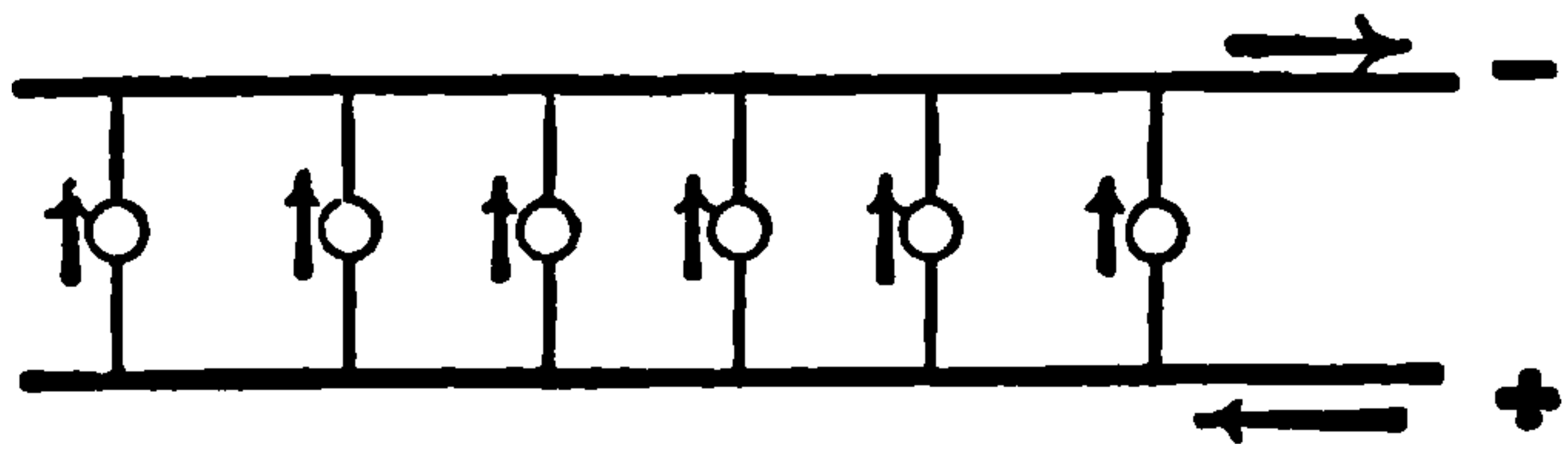


Fig. 238.

Three-wire systems, in which a third or neutral wire is introduced between the + and the − main, have been devised to enable higher voltages to be used, and thereby enable twice as many lamps to be lit with little additional expenditure in copper. To render the lamps on one side of the circuit (Fig. 239) independent of those on the other, in case an equal number do not happen to be switched on at the same time, the middle wire (which only need be thick enough to carry a current equal to the difference between the currents in the two outer wires) is carried back to the station and kept at mean potential between the two outer wires by the use of two dynamos instead of one.

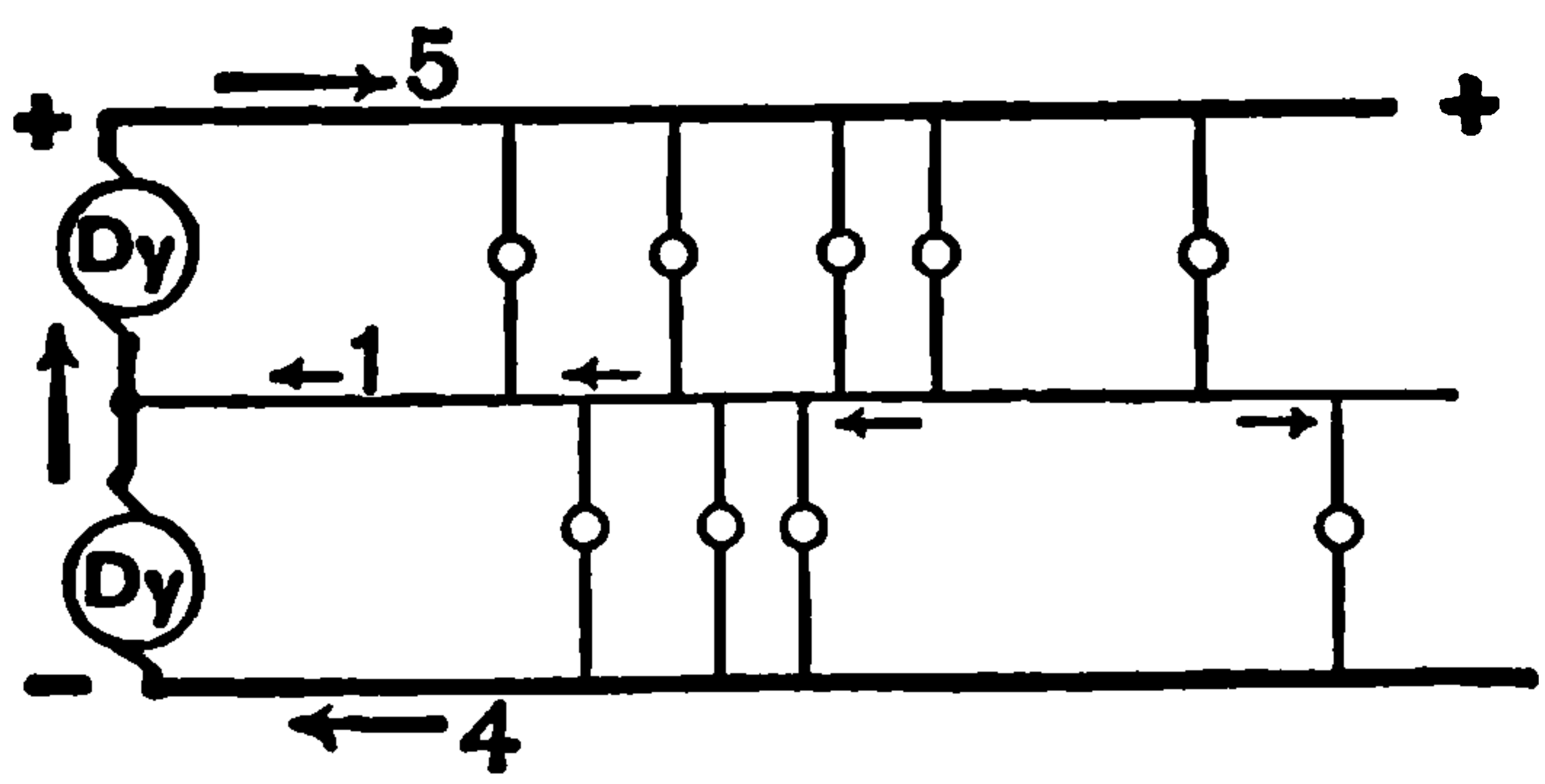


Fig. 239.

CHAPTER IX

INDUCTANCE

LESSON XL. — *Mutual Induction*

454. Mutual Induction. — Mutual induction between two circuits, a primary and a secondary, was briefly considered in Art. 224. Let us now consider the electromotive-forces so induced. Suppose the primary coil to have S_1 spirals, and the secondary coil S_2 spirals. At first let them be so arranged (by use of an iron core or by geometric juxtaposition) so that all the magnetic lines evoked by the primary coil pass through all the spirals of the secondary coil; both coils being placed close together upon a suitable core of laminated iron.

By Art. 377 the magnetic flux due to current C in the primary coil will be

$$N = 4\pi CS/_{1}10Z,$$

where Z is the reluctance (Art. 376) of the magnetic circuit. The total amount of cutting magnetic lines by the S_2 spirals of the secondary, when current C is turned off or on, will be

$$S_2N = 4\pi CS_1S_2/10Z.$$

Hence it follows that the amount of cutting of magnetic lines (*i.e.* the induction in the secondary circuit) due to turning on or off 10 amperes (= 1 C.G.S. unit of current) in the primary, will be $4\pi S_1S_2/Z$. This quantity

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of the secondary current could induce tertiary currents in a third closed circuit, and that variations in the tertiary currents might induce currents of a fourth order, and so on. A single sudden primary current produces two secondary currents (one inverse and one direct), each of these produces two tertiary currents, or four tertiary currents in all. But with alternating or periodic there are the same number of secondary and tertiary fluctuations as of primary; but the currents of the second, fourth, etc. orders will be inverse in the direction of their flow to those of the first, third, fifth, etc.

456. Lenz's Law.—In Art. 223 it was explained how an increase in the number of magnetic lines through a circuit (as by pushing in a magnet) tended to set up an inverse current, or one flowing in such a direction as is opposed to the magnetism. Similarly a decrease in the magnetic lines (as by withdrawing the magnet) tends to set up currents that will pull the magnet back. Again, in Art. 379, it was laid down that a circuit traversed by a current experiences a force tending to move it so as to include the greatest possible number of magnetic lines-of-force in the embrace of the circuit. But if the number of lines be increased, during the increase there will be an opposing (or negative) electromotive-force set up, which will tend to stop the original current, and therefore tend to stop the motion. If there be no current to begin with, the motion will generate one, which being in a negative direction, will tend to diminish the number of lines passing through the circuit, and so stop the motion. Lenz, in 1834, summed up the matter by saying that *in all cases of electromagnetic induction the induced currents have such a direction that their reaction tends to stop the motion which produces them.* This is known as Lenz's law: it is a particular case of the more general law applicable to all electromagnetic systems, namely, that *every action on such a system, which, in producing a change in its configuration or state, involves a transforma-*

tion of energy, sets up reactions tending to preserve unchanged the configuration or state of that system. (Compare Arts. 204 and 379.)

457. Eddy-Currents Induced in Masses of Metal. — In 1824 Gambey found that a compass-needle oscillating in its box came to rest sooner if the bottom of the box were made of metal than if of wood. Arago investigated the matter, and found a copper plate under the needle most effective in damping its motions. He then rotated a copper disk in its own plane underneath a compass-needle, and found that the needle was dragged round as by some invisible friction. A copper disk suspended over a rotating magnet was found to be dragged by it. Attempts were made to account for these phenomena — known as *Arago's rotations* — by supposing there to be a sort of magnetism of rotation, until Faraday proved them to be due to induction. A magnet moved near a solid mass or plate of metal induces in it currents, which, in flowing through it from one point to another, have their energy eventually frittered down into heat, and which, while they last, produce (in accordance with Lenz's law) electromagnetic forces tending to stop the motion. These currents, circulating wholly within the metal, are called **eddy-currents**. If a cube or ball of good conducting metal be set spinning between the poles of such an electromagnet as Fig. 182, and the current be suddenly turned on, the spinning metal stops suddenly. In a copper disk revolving between the poles of a magnet (Fig. 240) there is a pair of eddies in the part passing between the poles, and these currents tend to pull the disk back. In fact, any conductor moved forcibly across the lines of a magnetic field experiences a mechanical resistance due to the induced currents which oppose

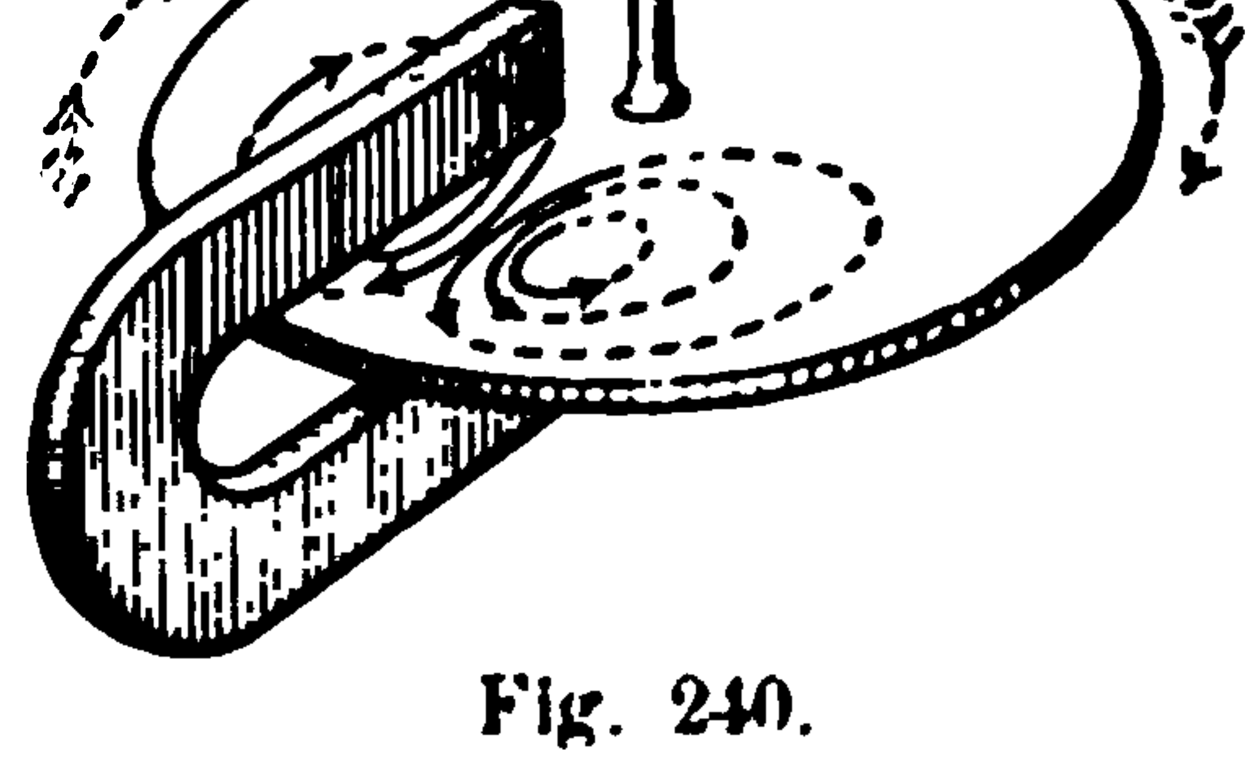


Fig. 240.

its motion. Foucault showed * that if, by sheer force, a disk be kept spinning between the poles of a powerful electromagnet it will become hot in consequence of the eddy-currents induced in it.

The eddy-current drag on a moving conductor (sometimes called the magnetic friction) is a force proportional to the speed and proportional to the square of the magnetic field; for the force (Art. 340) is proportional to the product of field and current, and the current (circulating round a given path) is proportional both to field and to speed. Hence eddy-current drag is employed in some forms of electric supply meter (Art. 442) to control the speed of the moving part.

Alternating electric currents also set up eddy-currents in masses of metal near them; for this reason the iron cores of transformers (Art. 480) and of dynamo armatures (Art. 463) must be carefully laminated, otherwise there will be heating and waste of energy.

Further, eddy-currents in any mass of metal between a primary and a secondary circuit will tend to set up in the secondary tertiary electromotive-forces opposing those set up by the primary. Hence interposed sheets of metal act as *induction-screens*.

LESSON XLI. — *Self-Induction*

458. Self-Induction. — It has been pointed out in Art. 224 how when a current in a circuit is increasing or diminishing, it exercises an inductive effect upon any neighbouring circuit; this inductive effect being due to the change in the magnetic field surrounding the varying current. But since the magnetic lines surrounding a current may, as they move inwards or outwards from the wire, cut across other parts of the *same* circuit, it is evident

* Hence some writers call the eddy-currents "Foucault's currents," though they were known years before Foucault's experiments were made.

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spirals) is $S \times N$, hence the induction when 10 amperes are turned on or off will be

$$L = 4\pi S^2/Z,$$

which may be expressed in henries by dividing by 10^9. If all the lines do not pass through all the spirals the value of L will be less than this.

The self-induced electromotive-force will depend upon the rate at which the current is changing; for if the total cutting SN take place in time t, it follows (Art. 225) that:—

$$E = -SN/t = -LC/t.$$

But since the rate at which the current changes is not uniform, E is also not uniform. If in an element of time dt the current charges by an amount dC, the rate of charge of the current is dC/dt, and the self-induced electromotive-force is $= -L \cdot dC/dt$.

The formal definition of the *henry* (Art. 354) is based on the above expression in order that it may apply to circuits with iron cores as well as to circuits without them.

The energy of the magnetic field surrounding the current is equal to $\frac{1}{2}LC^2$, since while the field is growing up to have LC lines in total, the average value of the current is $\frac{1}{2}C$.

To measure a coefficient of self-induction there are several methods:—

(*a*) *Alternate-Current Method.*—The volts V required to send current C at frequency n through coil having resistance R and coefficient of self-induction L are $V = C\sqrt{R^2 + 4\pi^2 n^2 L^2}$; or, if the resistance is negligible, $V = 2\pi n CL$, whence $L = V/2\pi n C$ (see Art. 472).

(*b*) *Bridge Methods.*—Of several bridge methods the best is Maxwell's. Let balance be obtained in usual way; key in battery circuit being put down before key in galvanometer circuit (Art. 415). Then press the keys in

reverse order, when the presence of self-induction in one of the four arms will upset balance, the needle giving a kick a proportional to the self-induction. Now introduce in the same arm an additional *small* resistance r, such that when keys are again operated in the usual order there is a small permanent deflexion δ. If the periodic time of swing of the needle be T the following formula then holds:— $L = Tra/2\pi\delta$.

(*c*) *Secohmmeter Method.*—Ayrton and Perry invented an instrument which alternately makes and breaks the battery circuit of the bridge and only allows the galvanometer to be in operation during a short interval of time T immediately after each making of the battery circuit (the galvanometer at other times being short-circuited). As the current is increasing during this interval, the self-induction L of a coil placed in one of the arms of the bridge acts as though there were an additional resistance r in that arm. The formula is then, $L = Tr$. As L is then the product of seconds and ohms, Ayrton and Perry proposed for the unit (now called the henry) the name of *secohm*.

459. Effects of Inductance.—The presence of inductance in a circuit affects the currents in several ways. The special *choking-effect* on alternate currents is dealt with in Art. 474. The effects on battery currents are also important. So long as the current is not changing in strength inductance has no effect whatever; but while the current is starting or while it is dying away the presence of inductance greatly affects it. In all cases inductance tends to oppose any change in the strength of the current; as may be foreseen from Lenz's law (Art. 456). When a current is increasing in strength inductance causes it to increase more slowly. When a current is dying away inductance tends to prolong it.

The existence of inductance in a circuit is attested by the so-called **extra-current**, which makes its appearance as a bright spark at the moment of breaking circuit. If

the circuit be a simple one, and consist of a straight wire and a parallel return wire, there will be little or no inductance; but if the circuit be coiled up, especially if it be coiled round an iron core, as in an electromagnet, then on breaking circuit there will be a brilliant spark, and a person holding the two ends of the wires between which the circuit is broken may receive a shock, owing to the high electromotive-force of this self-induced extra current. This spark represents the energy of the magnetic field surrounding the wire suddenly returning back into the circuit. The extra-current on "making" circuit is an inverse current, and gives no spark, but it prevents the battery current from rising at once to its full value. The extra-current on breaking circuit is a direct current, and therefore keeps up the strength of the current just at the moment when it is about to cease. To avoid the perturbing effects of inductance, resistance-coils are always coiled back upon themselves (Art. 414).

Even when a circuit consists of two parallel straight wires there is a magnetic field set up between them, giving inductive reactions. The coefficient of self-induction for two wires of length l and radius a at an axial distance b apart in air is

$$L = l\left(\frac{\mu}{2} + 4 \log_e \frac{b}{a}\right)10^{-9};$$

where L is in henries; a, b and l in centimetres, and μ the permeability of the wire.

460. Helmholtz's Equation. Time-constant.—From that which precedes it is clear that whenever a current is turned on there is a *variable period* while the current is growing up to the value which it will reach when steady, namely the value as determined by Ohm's law. But during the variable period Ohm's law is no longer applicable.

Von Helmholtz, who investigated mathematically the effect of self-induction upon the strength of a current,

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required by the current to rise to a certain fraction, namely $(\epsilon - 1)/\epsilon$, — or 0·634 — of its final value.

A very brief consideration will show that in those cases where the circuit is so arranged that the inductance L is small as compared with the resistance R, so that the time-constant is small, the term $\left(\epsilon^{-Rt/L}\right)$ will vanish from the equation for all appreciable values of t.

On the other hand if L is great compared with R, the current during its growth will be governed almost entirely by the inductance, and not by the resistance of the circuit, which will act as though its resistance were $= L/t$.

These matters are graphically depicted in Fig. 241, in which there are two curves of rise of current. Consider a circuit having E = 10 volts, R = 1 ohm, L = 10 henries. The steady current will be 10 amperes; but at the end of 1 second, as may be calculated by Helmholtz's equation, the current is only 0·95 of an ampere! In 2 seconds it is 1·81, in 5 seconds 3·95, in 10 seconds 6·34 amperes (see curve A). At the end of a whole minute it is only 9·975 amperes. Suppose now we increase the resistance to 2 ohms, and reduce the inductance to 5 henries. The final value of the current will be only 5 amperes instead of 10; but it will rise more quickly than before (see curve B). At the end of 1 second it will be 1·647 ampere, in 2 seconds 2·755, in 10 seconds 4·91 amperes. We conclude that for all apparatus that is required to be rapid-acting (relays, telephones, chronographs, etc.), it is much more important to keep down the inductance than the resistance of the circuit. We also see that the rule (Art. 407) so often given, about making the resistance of a battery equal to that of the rest of the circuit, is quite wrong for cases of rapid action. If the circuit has self-induction as well as resistance then it is better to group the cells of the battery so as to have higher resistance, namely put them all in series.

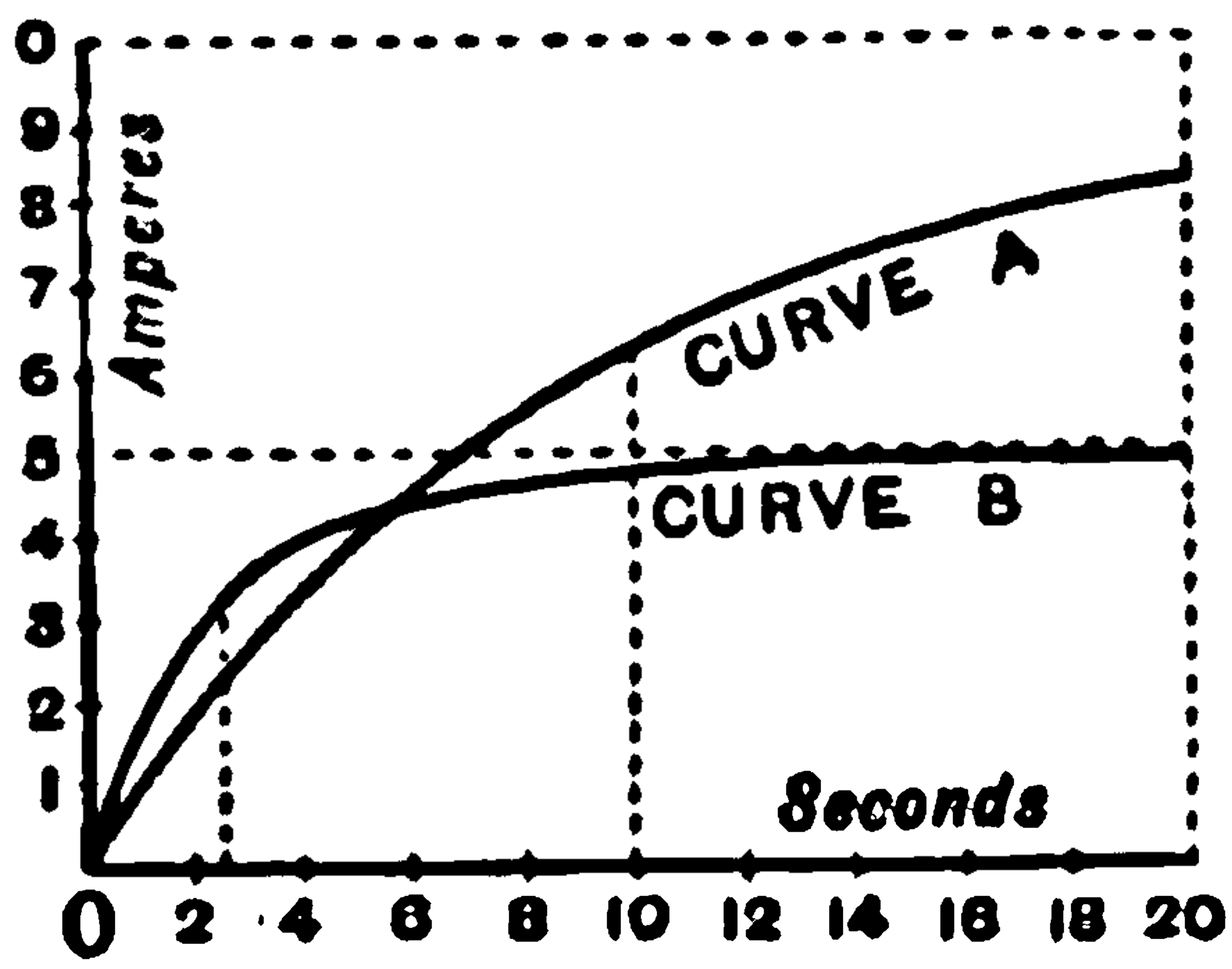


Fig. 241.

In fact everything goes on as though at time t after "make" there were two currents flowing in opposite directions at once; one the ordinary current flowing from the first at full strength, the other the extra-current having the value $-\frac{E}{R}\epsilon^{-Rt/L}$; the actual current being the difference between the two.

At "break" of circuit everything goes on as if, the ordinary current having dropped suddenly to zero, there was superposed an extra-current having the value $+\frac{E}{R}\epsilon^{-Rt/L}$; but here, since there is introduced into the circuit a resistance of unknown amount (the resistance along a spark being indefinite), the calculation becomes impracticable. We know that R is very great; hence we know that the variation will be more sudden, and that the self-induced E.M.F. at "break" is much greater than that at "make." The self-induced E.M.F. would be represented by the expression $E_t = E\epsilon^{-Rt/L}$. This expression should be compared with that for the E.M.F. of discharge of a condenser of capacity K through a resistance R (see also Art. 326), which is $V_t = V_0\epsilon^{-t/KR}$. From this it appears that in the case of a condenser discharge KR acts as the time-constant L/R does in the case of self-induction.

The actual quantity of electricity conveyed by the "extra-current" is equal to that which would be conveyed by current of strength E/R of lasting for time L/R; or $= EL/R^2$. At the "make" of the circuit the retardation causes the flow of electricity to be lessened by the amount $q = EL/R^2$. The energy which is stored up outside the wire while the current grows up from 0 to its final value C is equal to $\frac{1}{2}qE = \frac{1}{2}LC^2$.

CHAPTER X

DYNAMOS AND TRANSFORMERS

Lesson XLII. — *Magneto-electric and Dynamo-electric Generators*

461. Simple Magneto-electric Machines. — Faraday's discovery of the induction of currents in wires by moving them across a magnetic field suggested the construction of **magneto-electric machines** to generate currents in place of voltaic batteries, and Faraday himself constructed the first of such machines (Fig. 132) in 1831. In the early attempts of Pixii (1833), Saxton,

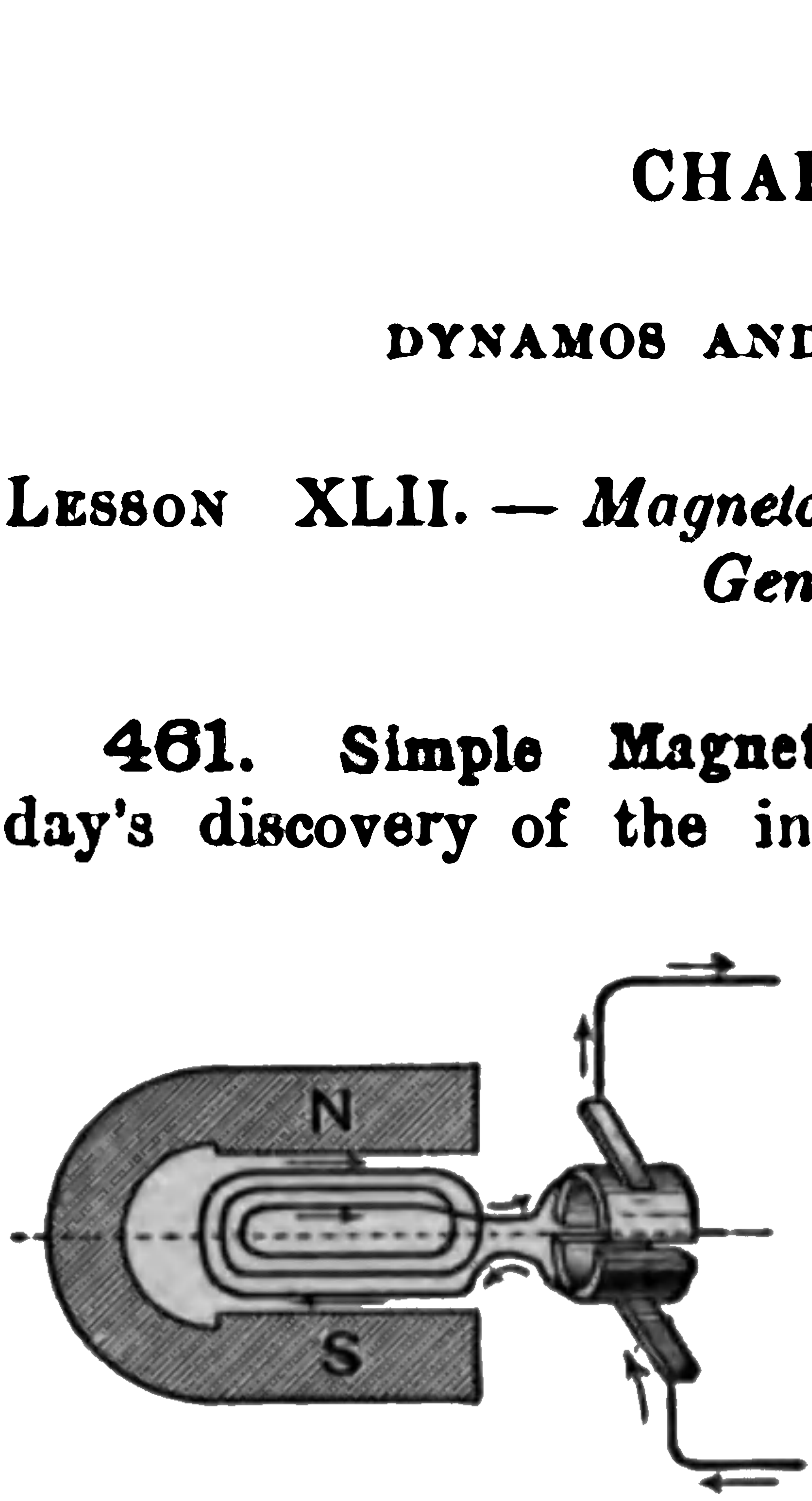


Fig. 242.

and Clarke, bobbins of insulated wire were fixed to an axis and spun rapidly in front of the poles of strong steel magnets. But, since the currents thus generated were alternately inverse and direct currents, a *commutator* (which rotated with the coils) was fixed to the axis to turn the successive currents all into the same direction. Fig. 242 illustrates the plan adopted by Sturgeon in 1836, using a split tube of copper to commute the connexion to the outer circuit at each half turn. In the figure the wire coil is supposed to be spun around a longi-

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electric machine, or, briefly, *dynamo*, is given to any machine for converting mechanical power into electrical power by the operation of producing relative motion between magnets and conductors. The part which acts as magnet is termed the *field-magnet*. In continuous-current generators it usually stands still; in some alternators it is made to revolve. Its function is to provide a large number of magnetic lines. The part which acts as the active conductor, cutting the magnetic lines and having electromotive-force induced in it is termed the *armature*. In continuous-current generators, the armature revolves between the poles of the field-magnet. In some alternators it is stationary. In the early machines the magnetism of the field magnets was independently excited. Various suggestions were made by Hjorth, Murray, S. A. Varley, and others to use the currents generated in the armature to excite the field-magnets. This was done in 1867 by Varley, Werner Siemens, and Wheatstone; the small current induced by the feeble residual magnetism being sent around the electromagnet to exalt its magnetism, and prepare it to induce still stronger currents. To machines so rendered self-exciting Werner Siemens gave the distinguishing name of dynamo-electric machines or generators, to distinguish them from the generators in which permanent steel magnets are employed. In either case the current is due to magneto-electric induction; and in either case also the energy of the currents so induced is derived from the dynamical power of the steam-engine or other motor which performs the work of moving the rotating coils of wire in the magnetic field. But the name has been extended to all generators, whether self-exciting or not. In all of them the electromotive-force generated is proportional to the number of turns of wire in the rotating armature, and to the speed of revolution. When currents of small electromotive-force, but of considerable strength are required, as for electroplating, the rotating armatures of a generator must be made with

small internal resistance, and therefore of a few turns of stout wire or ribbon of sheet copper. For producing currents at a high electromotive-force the armature must consist of *many* turns of wire or of rods of copper suitably connected, and it must revolve in a very powerful magnetic field.

463. Continuous-current Dynamos. — The dynamos of different makers differ in the design of their field-magnets and in the means adopted for securing continuity in the induced currents. Most continuous-current dynamos have a simple field-magnet with two poles: but many large machines are made with four, six, or eight poles. But the modern armature is complex. A simple coil, such as Fig. 242, with its 2-part commutator will not yield a steady current; for twice in each revolution the E.M.F. dies away to zero. The coils must be grouped so that some of them are always active. In most dynamos the armature winding is constructed as a *closed coil*, the wire being wound on a *ring* core of iron (Pacinotti's core with teeth, Gramme's core without teeth), or as a *drum* over a cylindrical core (Siemens's or Von Hefner's plan), or having the coils arranged flat as a *disk* (Desrozier's plan). In all these cases the convolutions are joined up so that (like the ring winding in Fig. 190) the coil is endless. If the current is brought in at one side of such a coil and taken out at the other side there will be two paths through the coil. As the coil spins between the poles of the magnet the electromotive-forces induced in the ascending and descending parts will tend to send the currents in parallel through these parts; and consequently contact-brushes must be set to take off the currents from the revolving coils at the proper places. The brushes are, however, set in contact not with the coils themselves but with a *commutator*, Fig. 244, consisting of a number of copper bars, insulated from one another, and joined on to the armature coil at regular intervals. Consider, for example, a Gramme ring made

as it were of a number of bobbins wound upon a ring core of iron wire. Each bobbin constitutes one section of the winding, and they are all joined together, the end of one section to the beginning of the next, and each such junction is joined down to a bar of the commutator. The current cannot pass from one bar of the commutator to the next without traversing the intervening section of

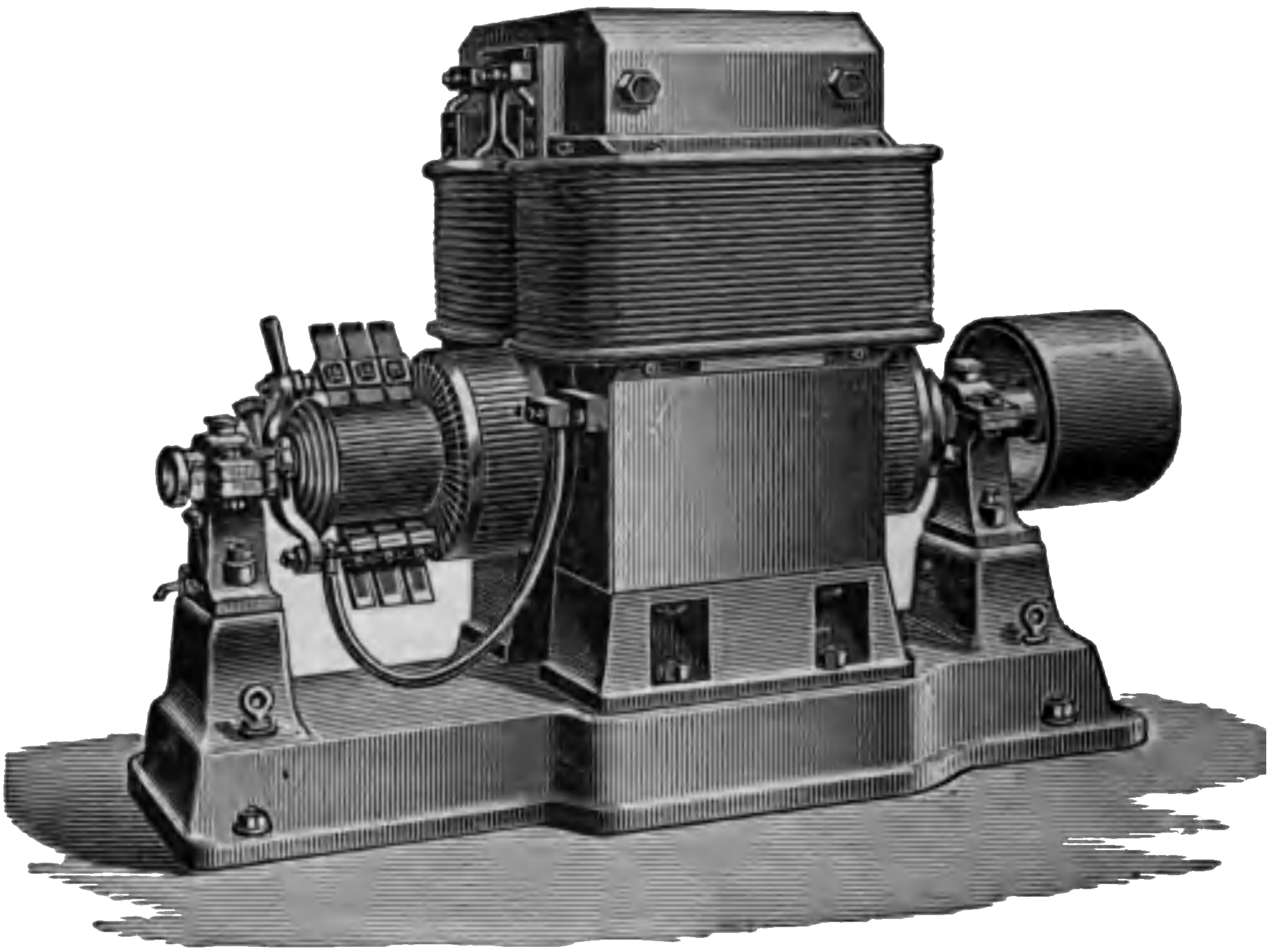


Fig. 245.

the windings. The commutator revolves with the armature; while the *brushes*, which are clamped in suitable holders, press against its surface, and are set in such a position that the current passes into them with as little sparking as possible. It is found that to prevent sparking the brushes must be set a little in advance of the diameter that is symmetrical between the poles: for the current in each section of the winding is reversed as it passes under the brush, and for sparkless reversal needs to

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volts at the terminals V will be less than the whole volts generated by an amount equal to rC, the lost volts.

$$V = E - rC.$$

As the electrical efficiency of the machine is the ratio V/E, it is evident that r should be as low as possible.

Example.—A dynamo having $N = 7{,}170{,}000$, $S = 120$, running at 780 revs. per min. (= 13 revs. per sec.) will generate an electromotive-force of 111 volts. If $r = 0·033$ ohm, then when $C = 210$ amperes, $rC = 7$ volts. Hence $V = 104$ volts.

The current C which a dynamo yields depends on the resistance, etc., of the circuit it supplies. The maximum current it can supply is limited by several considerations, such as the heating of its parts, the sparking at the brushes, which becomes serious if too much current is drawn from the machine, the mechanical strength of its parts, and also the power of the driving-engine.

The *gross output* of a dynamo is the number of amperes multiplied by the total electromotive-force generated, or CE. The *nett output* is the number of amperes multiplied by the volts at terminals, or CV. These numbers are turned to horse-power by dividing by 746.

The *commercial efficiency* of a dynamo is the ratio between the nett output and the mechanical power applied to drive the machine.

All the armature conductors of a dynamo are subject, when the machine is running, to a mechanical drag opposing the rotation. This is due to the action between the magnetic field and the current (Art. 340).

A little power is wasted by eddy-currents (Art. 457), and by hysteresis (Art. 368) in the armature core, and also a little by eddy-currents (Art. 463) in the moving masses of metal, so diminishing the efficiency: but in well-constructed machines such losses are slight.

To calculate the field-magnet windings the formulæ of

Arts. 377 and 399 must be applied (see exercise 21 on Chap. V.).

465. Excitation of Field-Magnets. — There are several modes of exciting the magnetism of the field-magnets, giving rise to the following classification: —

1. *Magneto Machine*, with permanent steel magnets.

2. *Separately-excited Dynamo;* one in which the currents used to excite the field-magnets are furnished by a separate machine called an "exciter."

3. *Separate-coil Dynamo*, with a separate coil wound on the armature to generate the exciting current.

4. *Series-Dynamo*, wherein the coils of the field-magnet are in series with those of the armature and the

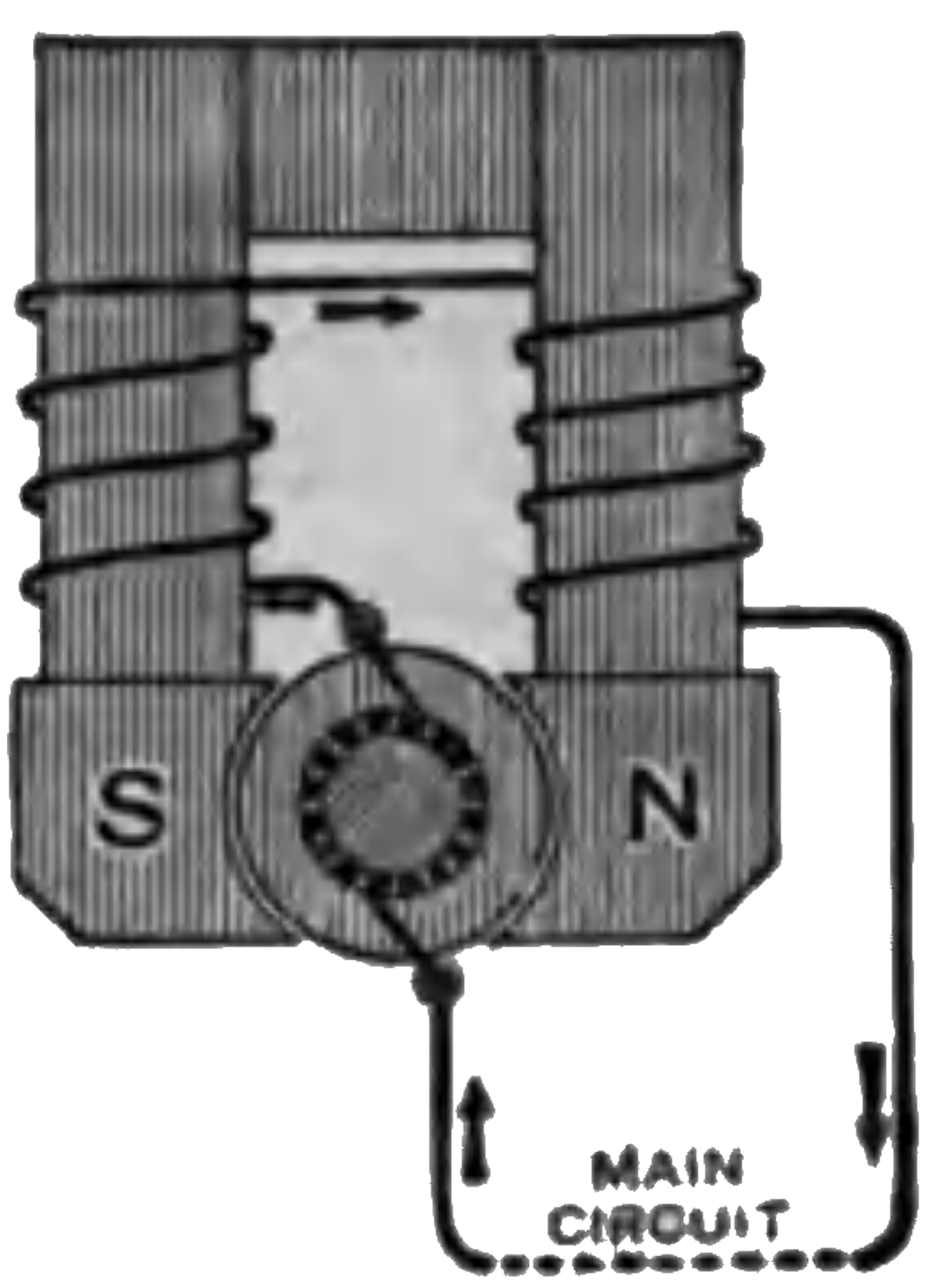


Fig. 246.

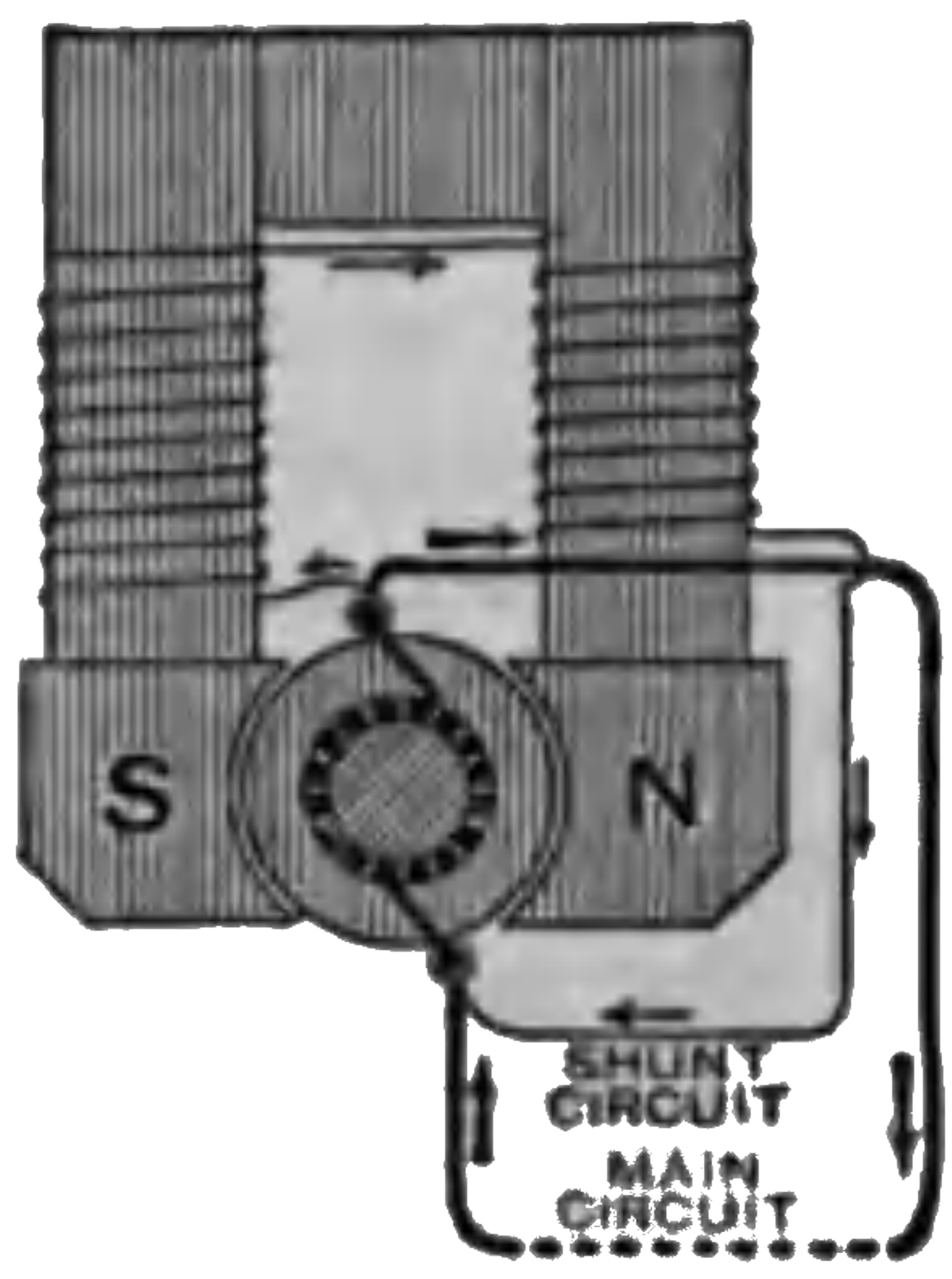


Fig. 247.

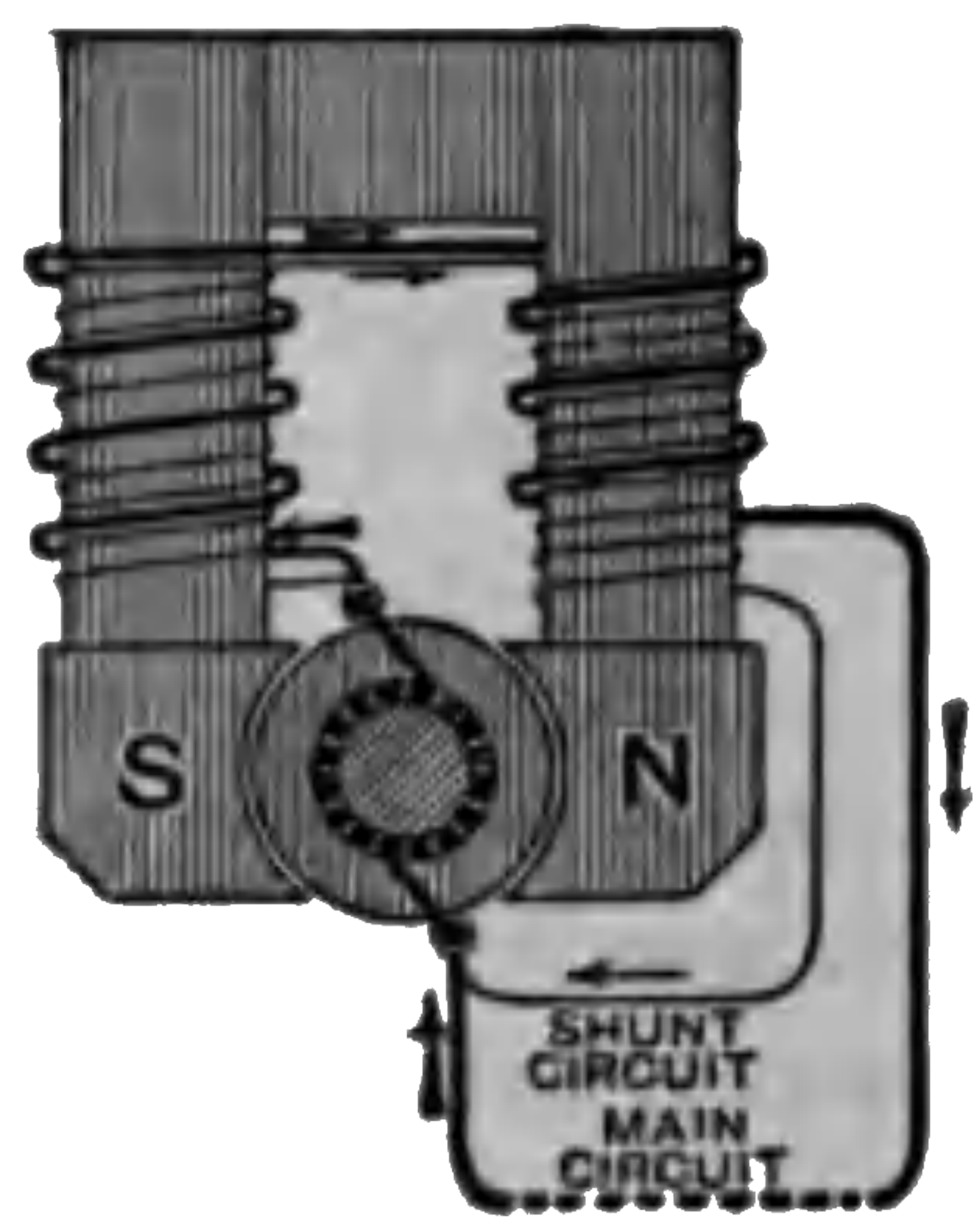


Fig. 248.

external circuit (Fig. 246), and consist of a few turns of thick wire.

5. *Shunt-Dynamo*, in which the coils of the field-magnet form a shunt to the main circuit; and, being made of many turns of thin wire, draw off only a small fraction of the whole current (Fig. 247).

6. *Compound-Dynamo*, partly excited by shunt coils, partly by series coils (Fig. 248).

The last three modes are illustrated in the accompanying diagrams. Each variety of winding has certain advantages depending on conditions of use.

466. Characteristic Curves.—To study the behaviour of various types of dynamo, Hopkinson devised the method of *characteristic curves*, wherein the two elements of output — the volts and the amperes — are plotted out. If a series-dynamo is examined with amperemeter and voltmeter, while run at constant speed on various loads, its performance will be found to give a curve like OQV in Fig. 249, where the external volts are plotted vertically, the amperes horizontally. This curve is the external characteristic. The volts rise as the current is increased, because of the increase of magnetization, but when this is near saturation they fall again because of internal resistance and sundry reactions. At any point such as Q the resistance of the external circuit is represented by the slope of the line QO (*i.e.* by the trigonometrical tangent of the angle QOX), since tan QOX is equal to QM/OM (= the volts divided by the amperes). If line OJ be drawn so that tan JOX is equal to the internal resistance, then MN will represent the lost volts when the current = OM. Adding to QM a piece PQ = MN, we obtain PM as the corresponding value of the total electromotive-force. In this way, from the curve OV we can construct the total characteristic OE. It will be evident that if the total resistance (*i.e.* the slope of the line OP) be increased P will come down the curve toward O, and there will be a certain point at which any further increase in the slope will produce a sudden drop of volts and amperes to almost zero. This is a peculiarity of series-machines; when running at a given speed they cease to yield any current if the resistance exceeds a certain critical value, depending in each machine on its construction.

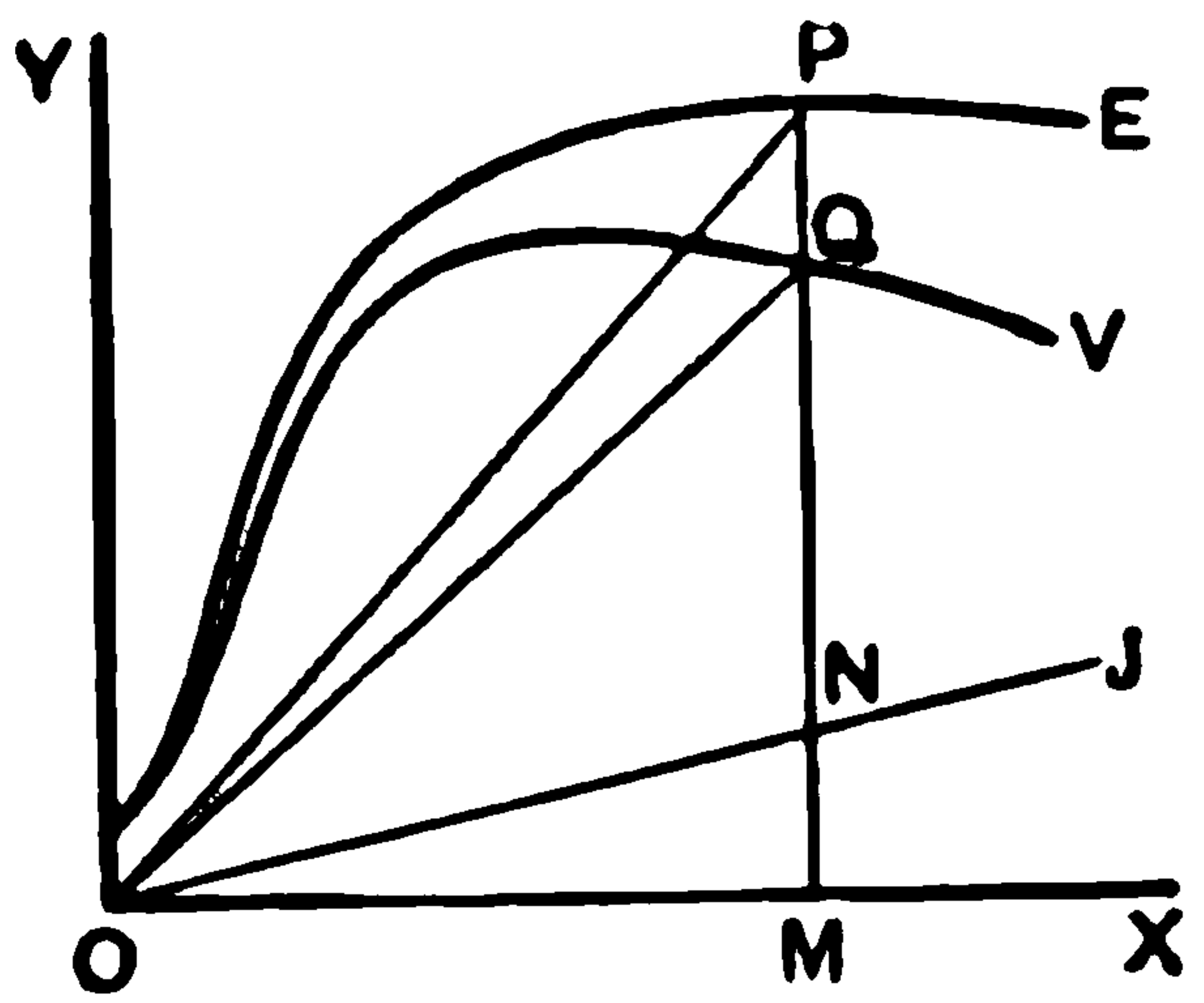


Fig. 249.

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quently, by using a *compound-winding*, consisting of a shunt-winding (to give the proper voltage an open circuit) and a few coils of thick wire, in series with the main circuit (to raise the excitation in proportion to the output), the voltage may be kept remarkably constant. By *over-compounding* with more series windings the dynamo may be made to maintain a constant voltage at some distant point in the circuit.

468. Constant Current Machines — Series Lighting. — To maintain an unvarying current in a series of lamps, as is frequently wanted for lighting with arc lamps (Art. 448), special dynamos are used known as *arc-lighting machines*. The best known of these are the Brush and the Thomson-Houston dynamos. Both have open-coil armatures (in which the coils are not grouped in a closed circuit), with special commutators, and automatic devices to regulate the output, the one by shunting the exciting current, the other by shifting the brushes. The current may thus be kept at 10 amperes, while the volts change (according to the number of lamps in circuit) from 50 to 2000 or more.

469. Unipolar Machines. — There is another class of dynamo-electric machines, differing entirely from any of the preceding, in which a coil or other movable conductor slides round one pole of a magnet and cuts the magnetic lines in a continuous manner without any reversals in the direction of the induced currents. Such machines, sometimes called "uni-polar" machines, have, however, very low electromotive-force, and are not practical. Faraday's disk-machine (Fig. 132) belonged to this class.

Lesson XLIII. — *Alternate Currents*

470. Periodic Currents. — We have seen that the revolving of a simple coil in a magnetic field sets up

electromotive-forces, which change in direction at every half-turn, giving rise to *alternate currents*. In each whole revolution there will be an electromotive-force which rises to a maximum and then dies away, followed immediately by a reversed electromotive-force, which also grows to a maximum and then dies away. Each such complete set of operations is called a *period*, and the number of periods accomplished in a second is called the *frequency* or *periodicity* of the alternations, and is symbolized by the letter n. In 2-pole machines n is the same as the number of revolutions per second; but in multipolar machines n is greater, in proportion to the number of pairs of poles. By revolving in a uniform field the electromotive-forces set up are proportional to the sine of the angle through which the coil has turned from the position in which it lay across the field. If in this position the flux of magnetic lines through it were **N**, and the number of spirals in the coil that enclose the **N** lines be called S, then the value of the induced electromotive-force at any time t when the coil has turned through angle θ ($= 2\pi nt$) will be

$$E_\theta = 2\pi n \mathrm{SN} \sin\theta \div 10^8,$$

or, writing D for $2\pi n\mathrm{SN}/10^8$, we have

$$E_\theta = \mathrm{D}\sin\theta.$$

In actual machines the magnetic fields are not uniform, nor the coils simple loops, so the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend on the shape of the polar faces, and on the form and breadth of the coils. But in most cases we are sufficiently justified in assuming that the impressed electromotive-force follows a sine law, so that the value at any instant may be expressed in the above form, where D is the maximum value or *amplitude* attained by E, and θ an angle of *phase* upon an imaginary circle of

reference. Consider a point P revolving clock-wise round a circle. If the radius of this circle be taken as unity, PM will be the sine of the angle θ, as measured from 0°. Let the circle be divided into any number of equal angles, and let the sines be drawn similarly for each. Then let these sines be plotted out at equal distances apart along the horizontal line, as in Fig. 251, giving us the sine curve.

In Fig. 251 one revolution of P around the circle of reference corresponds to one complete alternation or cycle

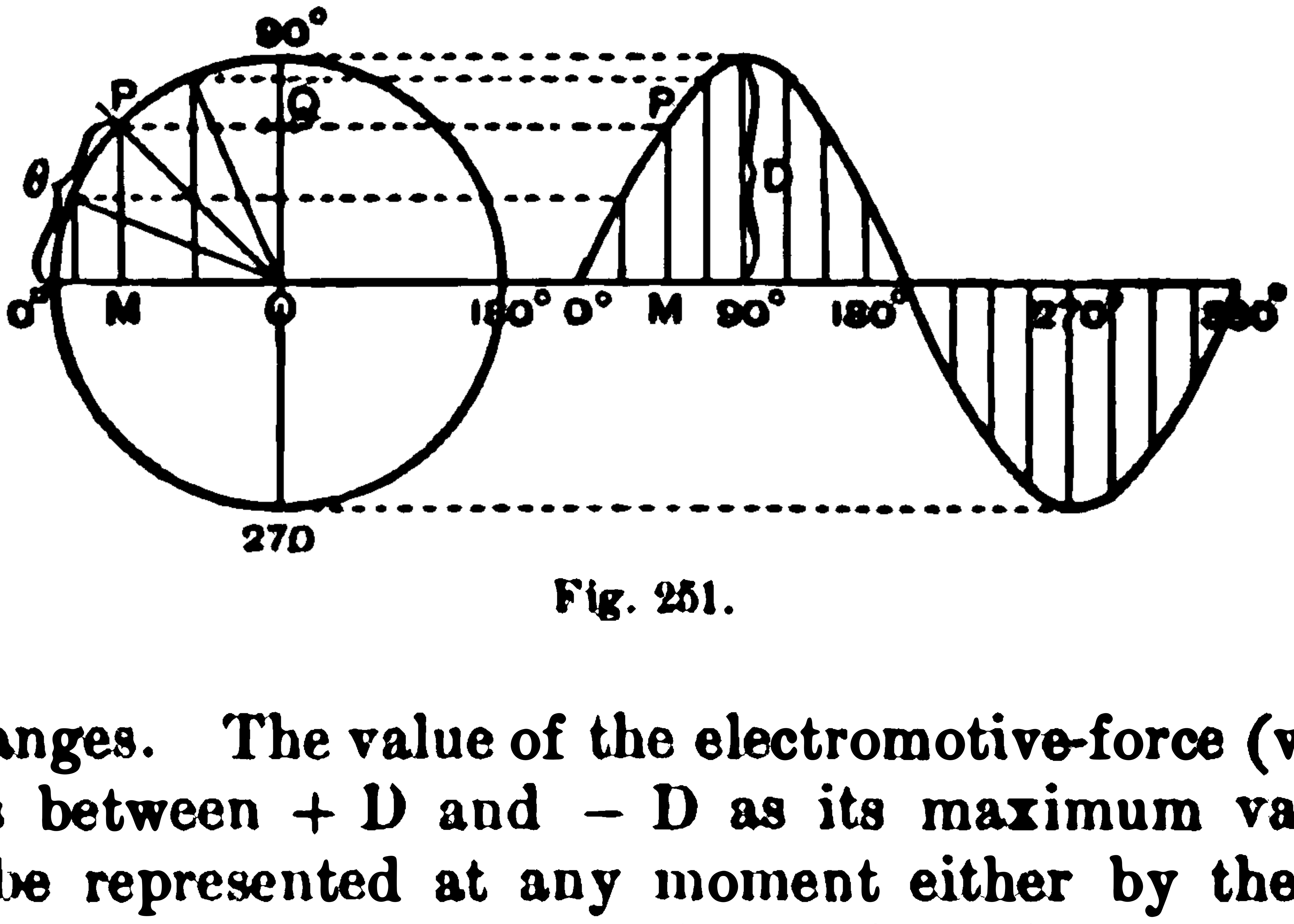


Fig. 251.

of changes. The value of the electromotive-force (which varies between + D and − D as its maximum values) may be represented at any moment either by the sine PM or by projecting P on to the vertical diameter, giving OQ. As P revolves, the point Q will oscillate along the diameter.

The currents which result from these periodic or alternating electromotive-forces are also periodic and alternating; they increase to a maximum, then die away and reverse in direction, increase, die away, and then reverse back again. If the electromotive-force completes 100 such cycles or reversals in a second, so also will the current.

471. Virtual Volts and Virtual Amperes.—Measuring instruments for alternate currents, such as electro-dynamometers (Art. 395), Cardew voltmeters (Art.

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sented by the blacker line, occur a little *later* than those of the volts. But inductance has another effect of more importance than any retardation of phase; it produces reactions on the electromotive-force, choking the current down. While the current is increasing in strength the reactive effect of inductance tends to prevent it rising. To produce a current of 40 amperes in a resistance of $1\frac{1}{2}$ ohms would require — for continuous currents — an E.M.F. of 60 volts. But an alternating voltage of 60 volts will not be enough if there is inductance in the circuit reacting against the voltage. The matter is complicated by the circumstance that the reactive impulses of electromotive-force are also out of step: they are in fact exactly a quarter period behind the current. If an alternate current of C (virtual) amperes is flowing with a frequency of n cycles per second through a circuit of inductance L, the reactive electromotive-force* will be $2\pi n$LC (virtual) volts. If, for example, $L = 0{\cdot}002$ henry, $n = 50$ periods per second, and $C = 40$ amperes, the reactive electromotive-force will be 25·1 volts. Now if we wish to drive the 40 (virtual) amperes not only through the resistance of $1\frac{1}{2}$ ohms but against this reaction, we shall require more than 60 volts. But we shall not require $60 + 25{\cdot}1$ volts, since the reaction is out of step with the current. Ohm's law is no longer adequate. To find out what volts will be needed we have recourse to geometry.

Plot out (Fig. 253) the wave-form O A*bd*, to correspond to the volts necessary to drive the current through the resistance, if there were no inductance. The ordinate *a*A may be taken to scale as 60. This we may call the current curve. Then plot out the curve marked $-p$LC to represent the volts needed to balance the reaction of

* This is calculated as follows. From Art. 458. $E = L dC/dt$. Now C is assumed to be a sine function of the time having instantaneous value $C_0 \sin 2\pi nt$; where C_0 is the maximum value of C. Differentiating this with respect to time we get $dC/dt = 2\pi n C_0 \cos 2\pi nt$. The "virtual" values of cosine and sine being equal we have for E the value $2\pi n$LC, but differing by $\frac{1}{4}$ period from the current in phase.

the inductance. Here p is written for $2\pi n$. The ordinate at O is 25·1; and the curve is shifted back one quarter of the period: for when the current is increasing at its greatest rate, as at O, the self-inductive action is greatest. Then compound these two curves by adding

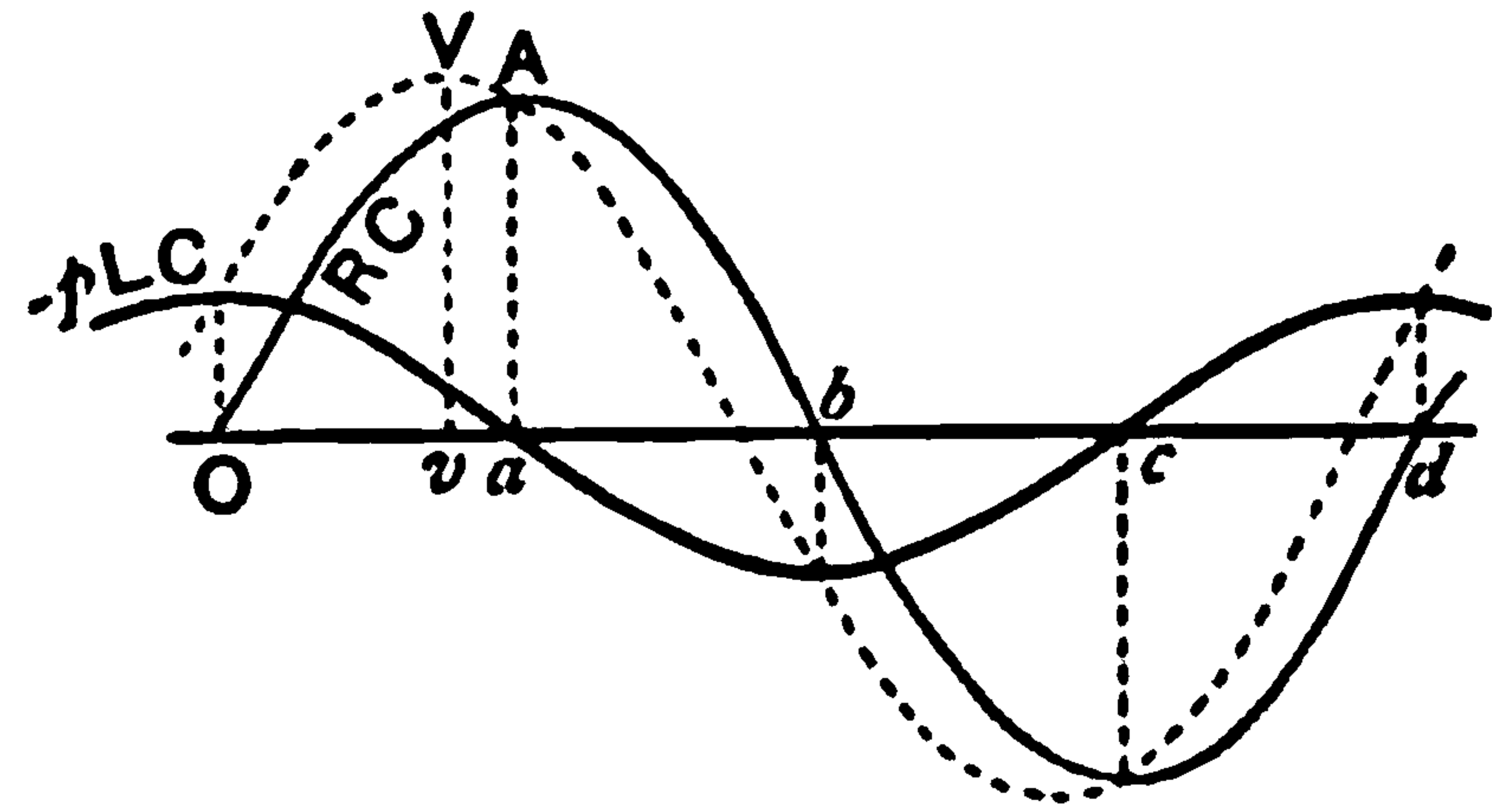


Fig. 253.

their ordinates, and we get the dotted curve, with its maximum at V. This is the curve of the volts that must be impressed on the circuit in order to produce the current. It will be seen that the current curve attains its maximum a little after the voltage curve. The current lags in phase behind the volts. If Od is the time of one complete period, the length va will represent the time that elapses between the maxima of volts and amperes. In Fig. 254 the same facts are represented in a revolving diagram of the same sort as Fig. 251. The line OA represents the working volts R × C, whilst the line AD at right angles to OA represents the self-induced volts pLC. Compounding these as by the triangle of forces we have as the impressed volts the line OD. The projections of these 3 lines on a vertical line while the diagram revolves around the centre O give the instantaneous values of the three quantities. The angle AOD, or ϕ, by which the current lags behind the impressed volts is termed the

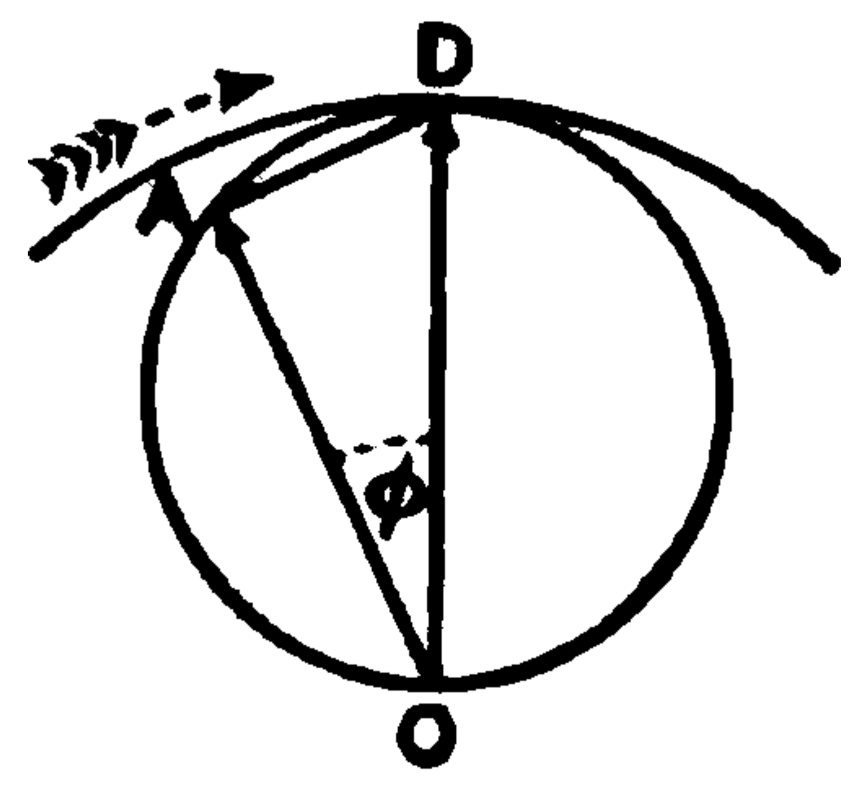


Fig. 254.

angle of lag. However great the inductance or the frequency, angle ϕ can never be greater than 90°. If OA is 60 and AD is 25·1, OD will be 65 volts. In symbols, the impressed volts will have to be such that $E^2 = (RC)^2 + (pLC)^2$. This gives us the equation:—

$$C = \frac{E}{\sqrt{R^2 + p^2L^2}}.$$

The denominator which comes in here is commonly called *the impedance.*

473. Maxwell's Law.—In Figs. 255 and 256 the angle of lag is seen to be such that $\tan \phi = pLC/RC$ or



Fig. 255. Fig. 256.

$= pL/R$. And it is evident that the effect of the inductance is to make the circuit act as if its resistance instead of being R was increased to $\sqrt{R^2 + p^2L^2}$. In fact the alternate current is governed not by the resistance of the circuit but by its impedance. At the same time the current is lagging as if the angle of reference were not θ but $\theta - \phi$, so that the equation for the instantaneous values of C, when $E = D \sin \theta$, is

$$C = \frac{D \sin (\theta - \phi)}{\sqrt{R^2 + p^2L^2}}.$$

This is Maxwell's law for periodic currents as retarded by inductance. As instruments take no account of phase but give virtual values the simpler form preceding is usually sufficient.

The effect of capacity introduced into an alternate current circuit is to produce a *lead* in phase, since the reaction of a condenser instead of tending to prolong the

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power supplied to a motor, or other part of an alternate current circuit, we measure separately with amperemeter and voltmeter the amperes and volts, and then multiply together the readings we obtain as the *apparent watts* a value often greatly in excess of the *true watts*, owing to the difference in phase, of which the instruments take no account. The true power (watts) is in reality $W = CV \cos \phi$, where C and V are the virtual values, and ϕ the angle of lag. But the latter is usually an unknown quantity. Hence recourse must be had to a suitable watt-meter; the usual form being an electrodynamometer (Art. 438) specially constructed so that the high-resistance circuit in it shall be non-inductive.

Whenever the phase-difference (whether lag or lead) is very large the current, being out of step with the volts, is almost *wattless*. This is the case with currents flowing through a choking coil or into a condenser, if the resistances are small.

476. High Frequency Currents. — The reactive effects of inductance and capacity increase if the frequency is increased. The frequency used in electric lighting is from 50 to 120 cycles per second. If high frequencies of 1000 or more cycles per second are used the reactions are excessive. In such cases the currents do not flow equally through the cross-section of the conducting wire, but are confined mainly to its outer surface, even thick rods of copper offering great impedance. Even at a frequency of 100 the current at a depth of 12 millimetres from the surface is (in copper) only about $\frac{1}{3}$ of its value in the surface layers. In iron wires the depth of the skin for $\frac{1}{3}$ value is about 1 millimetre. For such rapid oscillations as the discharge of a Leyden jar, where the frequency is several millions, the conducting skin is probably less than $\frac{1}{100}$ of a millimetre thick. Hollow tubes in such cases conduct just as well as solid rods of same outer diameter. The conductance is proportional not to section but to perimeter.

Whenever a current is not distributed equally in the cross-section of any conductor there is a real increase in the resistance it offers; the heating effect being a minimum when equally distributed. The fact that the oscillatory currents are greatest at the skin gives the strongest support to the modern view that the energy in an electric circuit is transmitted by the surrounding medium and not through the wire (see Art. 519 on energy-paths).

477. Alternate-current Electromagnets.—When an alternate current is sent through a coil it produces an alternating magnetic field. An iron core placed in the alternating field will be subjected to a periodic alternating magnetization. Electromagnets for alternate currents must have their iron cores laminated to avoid eddy currents; and owing to their choking action are made with fewer turns of wire than if designed for continuous currents of equal voltage. They repel sheets of copper owing to the eddy currents which they set up in them; the phase of these eddy currents being retarded by their self-induction. Elihu Thomson, who studied these repulsions, constructed some motors based on this principle. A solenoid, with a laminated iron plunger, if supplied with alternate currents at constant voltage, has the remarkable property of attracting the core with much greater force when the core is protruding out than when it is in the tube. This also is owing to the choking action.

LESSON XLIV.—*Alternate-current Generators*

478. Alternators.—The simple alternator (Fig. 243), with its two slip-rings for taking off the current, is merely typical. In practice machines are wanted which will deliver their currents at pressures of from 1000 to 5000 volts, with frequencies of from 50 to 120 cycles per second.

Slower frequencies are unsuitable for lighting, though applicable for power transmission. High voltages are common with alternate currents because (when using transformers) of the economy (Art. 447) thereby effected in the copper mains. Under these conditions almost all alternators are designed as multipolar machines; and as the perfect insulation required in the armatures is more readily attained if these parts are stationary it is common to fix them, and instead to rotate the field-magnet. The latter is separately excited with a small continuous current led in through slip-rings. One advantage of alternate current machines over continuous current dynamos is that there is no commutator.

Amongst the various types of alternators may be mentioned the following:—(1) Magnet rotating internally and consisting of a number of poles, alternately N and S, pointing radially outwards; armature external, fixed, and consisting of a number of coils wound either upon an iron ring (Gramme), or upon inwardly projecting iron poles (Ganz), or set against the inner face of an iron core (Elwell-Parker), or embedded in holes just within the face of an iron core (Brown). In all cases where iron cores are used in armatures it is carefully laminated. (2) Magnet fixed externally and consisting of a number of alternate poles pointing radially inwards; armature internal, revolving, consisting of a number of coils wound either upon the surface of a cylindrical iron core (Westinghouse, Thomson-Houston) or fixed upon radially projecting poles (Hopkinson). (3) Magnet fixed externally and consisting of two crowns of alternate poles, alternately N and S, projecting toward one another and nearly meeting, so making a number of magnetic fields between them; armature revolving, and without iron, consisting of a number of flat coils mounted together as a sort of star disk, revolve in the narrow gaps between the poles (Siemens, Ferranti).

Another form, known as Mordey's alternator, largely

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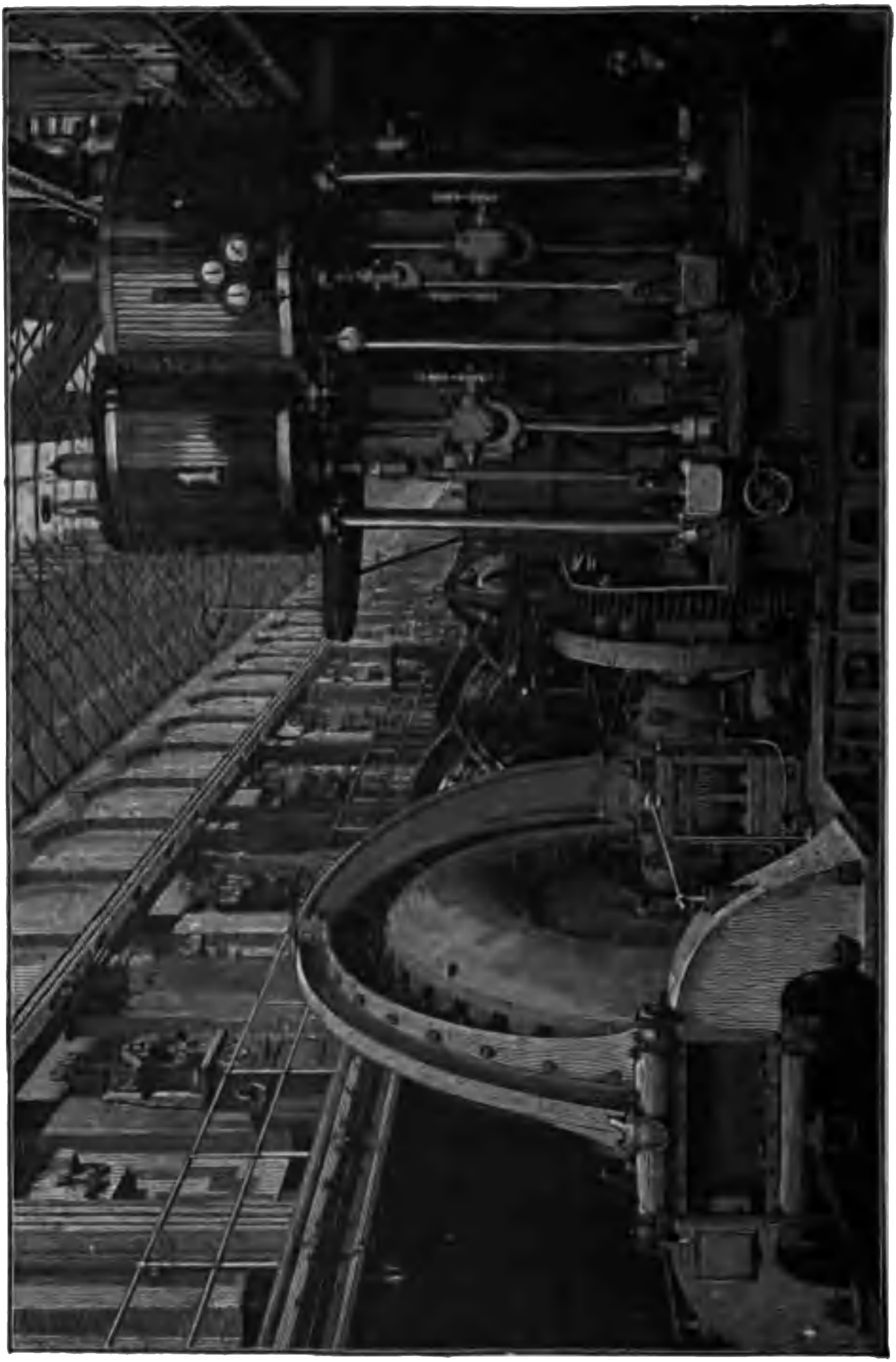


Fig. 260. — Central Generating Station of the City of London Electric Lighting Company.

479. Coupling of Alternators.—In the use of two or more alternators on one circuit a peculiarity arises that does not exist with continuous-current dynamos, owing to differences of phase in the currents. If two alternators driven by separate engines are running at the same speed and at equal voltage, it will not do to join their circuits by merely switching them to the mains if they are not also *in phase* with one another; or serious trouble may occur. In central station work it is usual to run several machines all in parallel. Now if two machines are feeding into the same mains each is tending to send current back to the other; and if their electromotive-forces are at any instant unequal, that with the greater will tend to send its current the opposite way through the other. To explain what occurs consider Fig. 261, which is a revolving diagram of the same kind as Figs. 251 and 254. If the two alternators are

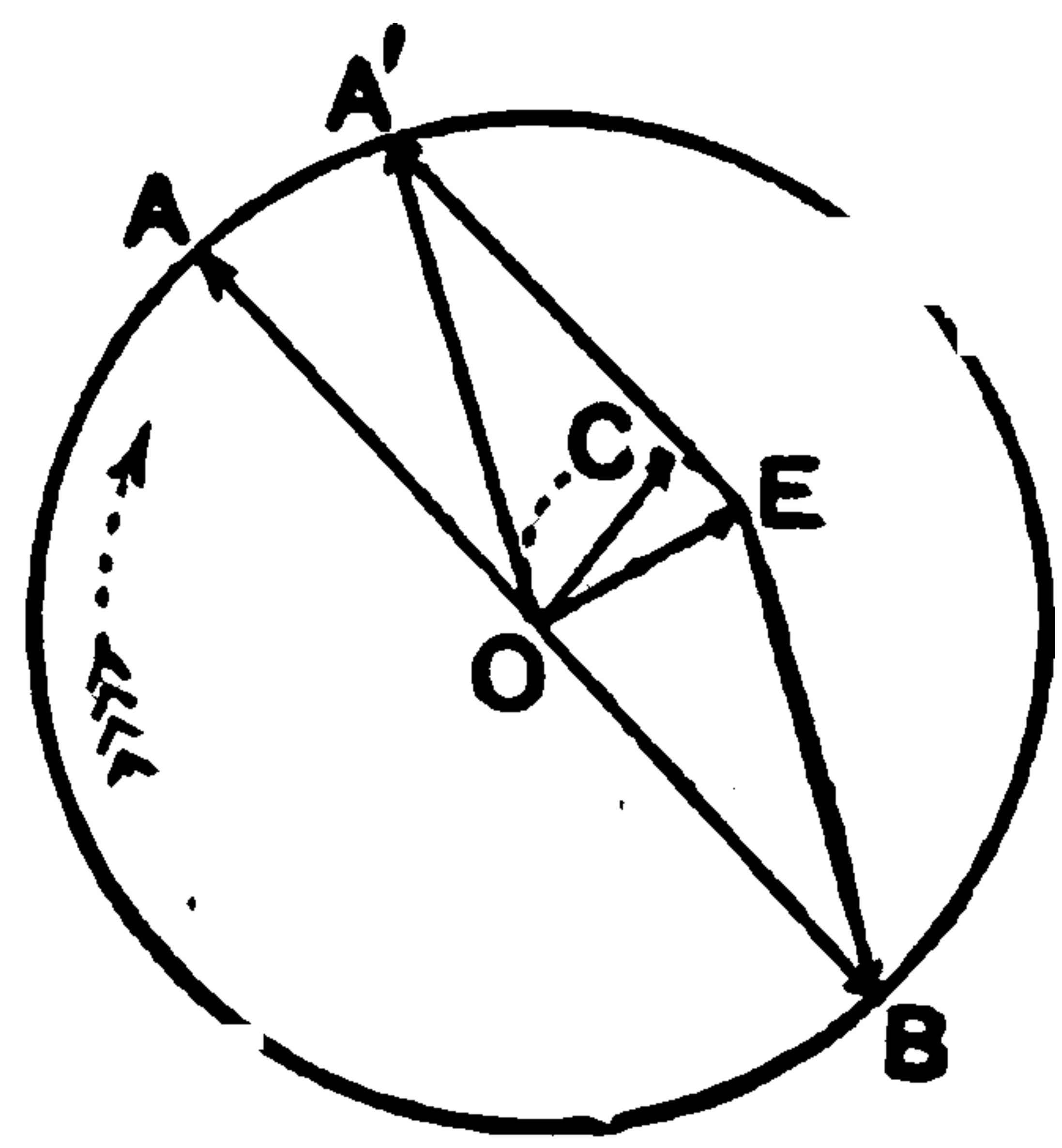


Fig. 261.

exactly in step, they will both be sending a pulse of current toward the mains at the same moment, but, so far as the circuit connecting them is concerned, these impulses will be exactly opposed. Let OA and OB represent these two exactly opposed impulses. Now suppose one of the two machines to gain a little on the other, OA shifting forward to OA′. The two electromotive-forces no longer balance, but will have a resultant OE tending to make a current oscillate through the two machines, this current being out of phase both with the leading machine A and with the lagging machine B. But this local current will itself lag a little in phase behind OE because of the inductance in its path. Let the phase of the current then be indicated by OC, which is set back a little. There is now a current surging to and fro between the two machines, and it is obviously more nearly in phase with

OA than with OB. This means that in the machine A the volts and amperes are more nearly with one another than in the lagging machine B. ence to Arts. 436 and 445 will at once show that rent is helping to drive B as a motor, and that mechanical effort will be thrown on A, which i more as a generator. Hence this interchange of tends automatically to bring up the lagging macl to load the leading machine. They will come b phase. All alternators of good construction driven will run together in parallel, even thou electromotive-forces are unequal. On the other two alternators are joined in series, the resulting when they are ever so little out of phase, tends to lagging machine and hasten the leading one till into complete opposition of phase, one running en generator, the other entirely as motor. This is for transmission of power from an alternator at of a line to a synchronous alternator at the otl two machines keep step at all loads. But they run together in series if both are to act as gei unless rigidly coupled together on the same shaft

To prevent accidents arising from too sudden fer of current between two machines it is usual in stations to employ a *synchronizer*, a device to indi phases of the alternations. When an alternator switched into circuit (in parallel with one or more the operator does not turn the switch until (sp volts being both right) the electromotive-force machine has come exactly into identical phase w of the circuit into which it is to be introduced.

Lesson XLV. — *Transformers*

480. Alternate-current Transformers. — Tra ers are needed in the distribution of curren distance, because glow-lamps in the houses n

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in diagram the use of transformers on a distributing system.

481. Elementary Theory of Transformers. — If the primary volts are maintained constant, the secondary volts will be nearly constant also, and the apparatus becomes beautifully self-regulating, more current flowing into the primary of itself when more lamps are turned on in the secondary circuit. This arises from the choking effect of self-induction in the primary. If no lamps are on the secondary circuit the primary coil simply acts as a choking-coil. When all the lamps are on the primary acts as a working-coil to induce currents in the secondary. When only half the lamps are on the primary acts partly as a choking-coil and partly as a working-coil.

Let V_1 be the volts at the primary terminals, V_2 those at the secondary terminals; S_1 the number of turns in the primary coil, S_2 the number in the secondary; r_1 the internal resistance in the primary, r_2 that of the secondary. Call the ratio of transformation $k = S_1/S_2$. The alternations of magnetism in the core will set up electromotive-forces E_1 and E_2 in the two coils strictly proportional to their respective numbers of turns (if there is no magnetic leakage); so $E_2 = E_1/k$; and since (apart from small hysteresis losses) $E_1C_1 = E_2C_2$, it follows that $C_1 = C_2/k$. The volts lost in primary are r_1C_1, those in secondary r_2C_2. Hence we may write

$$V_1 = E_1 + r_1C_1,$$
$$V_2 = E_2 - r_2C_2.$$

Writing the first as $E_1 = V_1 - r_1C_1 = V_1 - r_1C_2/k$, and inserting E_1/k for E_2 in the second equation, we get

$$V_2 = \frac{V_1}{k} - \left(\frac{r_1}{k^2} + r_2\right)C_2;$$

which shows that everything goes on in the secondary as

though the primary had been removed, and we had substituted for V_1 a fraction of it in proportion to the windings, and at the same time had added to the internal resistance an amount equal to the internal resistance of the primary, reduced in proportion to the square of the ratio of the windings. We also see that to keep the secondary volts constant the primary generator must be so regulated as to cause the primary volts to rise slightly when much current is being used. The currents in the two coils are in almost exact opposition of phase; they reach their maxima at the same instant, flowing in opposite senses round the core. The efficiency of well constructed transformers is very high, the internal losses being a very small percentage of the working load.

482. Continuous-current Transformers (Motor-dynamos). — To transform continuous currents from one voltage to another it is necessary to employ a rotating apparatus, which is virtually a combination of a motor and a generator. For example, a motor receiving a current of 10 amperes at 1000 volts may be made to drive a dynamo giving out nearly 200 amperes at 50 volts. Instead of using two separate machines, one single armature may be wound with two windings and furnished with two commutators; the number of turns in the windings being proportioned to the voltages, and their sectional areas to the amperes. Such *motor-dynamos* are in use. The elementary theory of these is the same as that in Art. 481, E_1 and E_2 now standing for the electromotive-forces respectively induced in the two windings on the revolving armature.

483. Continuous-alternate Transformers. — Revolving machinery equivalent to a combination of a continuous-current dynamo and an alternator may be used to transform continuous currents into alternating, or *vice versa*, one part acting as motor to drive, the other as generator. In this case also two separate machines need not always be used. Fig. 263 represents in diagram

a simple rotating armature having both a split-tube commutator to collect continuous currents, and a pair of slip-rings or alternating currents. Such a machine may convert continuous currents into alternating, or alternating into continuous. Or it may act as a motor if supplied with either kind of current; or may, if driven mechanically, generate both kinds of current at the same time.

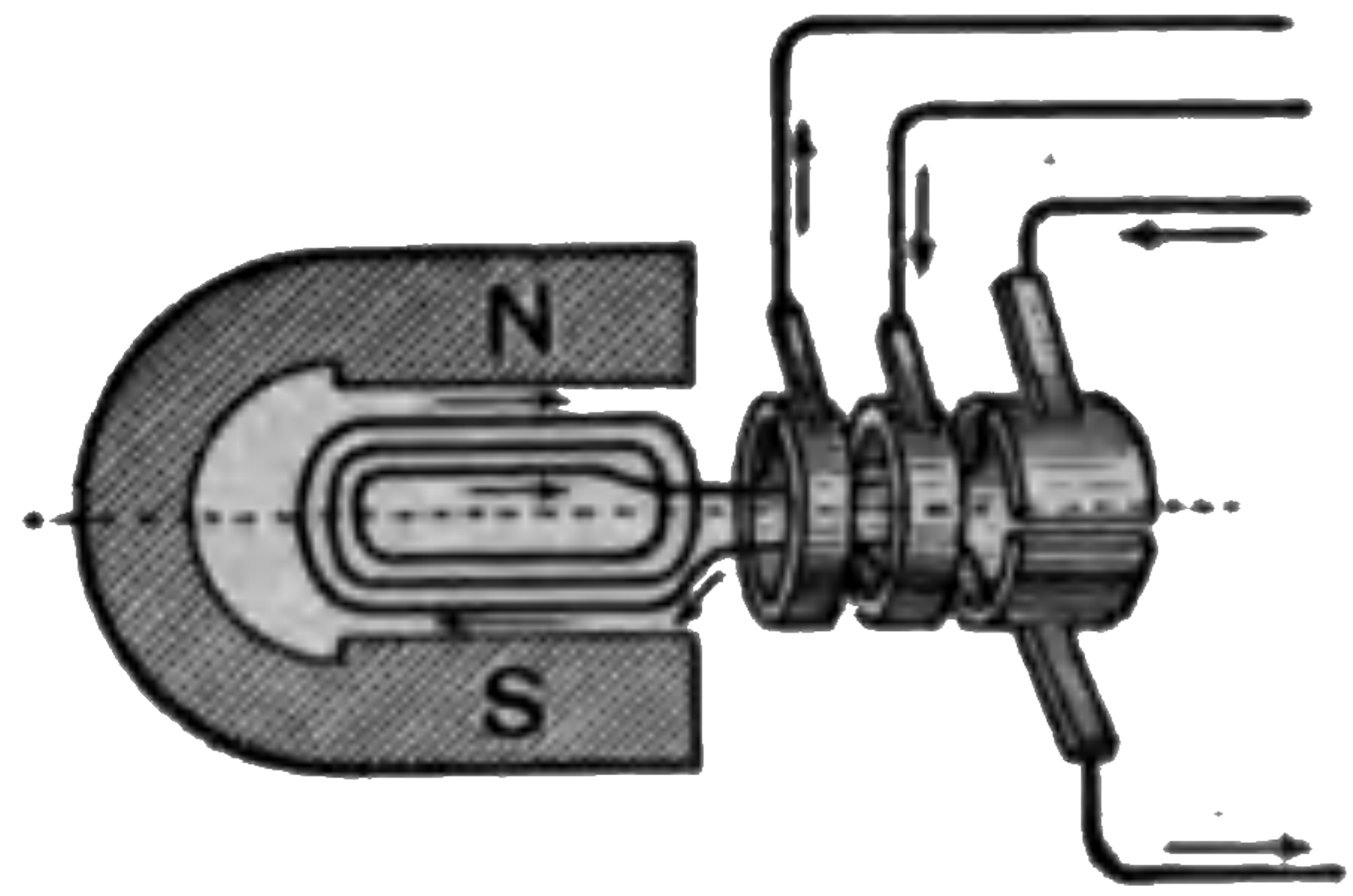


Fig. 268.

Lesson XLVI. — *Alternate-current Motors*

484. Alternate-current Motors. — We have seen (Art. 479) that one alternator can drive another as a motor, the two machines in series working in synchronism. There are two disadvantages in such motors — (i.) that they are not self-starting, but must be brought up to speed before the current is applied; (ii.) that their field-magnets must be separately excited. Other forms of motor have consequently been sought. Ordinary continuous-current motors, if made with laminated iron magnets, will work, though not well, with alternating currents.

The modern alternate-current motor has developed from the proposals of Borel (1887), Ferraris (1888), and Tesla (1888) to employ two or more alternating currents in different phases.

485. Polyphase Currents. — It is obviously possible, by placing on the armature of an alternator two separate sets of coils, one a little ahead of the other, to obtain two alternate currents of equal frequency and strength, but differing in phase by any desired degree. Gramme, indeed, constructed alternators with two and

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into the ring at the points A B C. The current flows in first at A (and out by B and C), then at B (flowing out by C and A), then at C (out by A and B), again producing a revolving magnetic field. This is analogous to a 3-crank engine, with the crank set at 120° apart.

There are several ways of combining the circuits that receive the currents of the various phases. For example, the windings of Fig. 264 might be divided into four separate coils, each having one end joined to a common junction, and the four outer ends joined respectively to the four line wires. Or the windings of Fig. 265 might be arranged as three separate coils, each having one end joined to a common junction, and with the three outer ends joined respectively to the three line wires. Such arrangements would be called *star* groupings, as distinguished from the *mesh* groupings of the cuts. Also the coils, in whichever way grouped, need not be wound upon a ring. The two-phase coils of Fig. 264 might be wound upon four inwardly-projecting pole-pieces; and the three-phase coils of Fig. 265 might be wound upon three inwardly-projecting pole-pieces. Or in larger multipolar machines a three-phase set of coils might be arranged upon a set of six, nine, twelve, or more poles, in regular succession.

486. Properties of the Rotatory Field—Asynchronous Motors.—In such rotating magnetic fields masses of metal at once begin to rotate. A magnet or mass of iron, pivoted centrally, can take up a synchronous motion, but may require to be helped to start. Any pivoted mass of good conducting metal, such as copper, will also be set in motion, and will be self-starting, but will not be synchronous. In such a centred mass, or *rotor*, eddy-currents are set up (just as in Arago's rotations, Art. 457), which drag the metal mass and tend to turn it. The strength of these currents in the rotating part depends on the relative speed of the field and the rotor. If the rotor were to revolve with speed equal to

the revolving field, the eddy-currents would die away, and there would be no driving force. The rotor actually used in such motors consists of a cylindrical core built up of thin iron disks, over which is built up a sort of squirrel cage of copper rods joined together at their ends into a closed circuit. In some forms (designed by Brown) the rods are inserted in holes just below the surface of the core. The revolving part has no commutator or slip-rings, and is entirely disconnected from any other circuit. It receives its currents wholly by induction. Such *asynchronous motors* start with considerable torque (or turning moment) and have a high efficiency in full work. Similar motors for use with ordinary or single-phase alternate currents are now in use. To start them it is necessary to split the alternate current into two currents differing in phase. This is done by the use of a divided circuit, in the two branches of which different reactances are introduced. If in one branch there is a choking coil to offer inductance, the current in that branch will be retarded; if in the other there is a condenser, the current in this branch will be accelerated in phase. Combining these two currents a rotatory field is produced for starting the movement. When once the motor has started a further turn of the switch simply puts on the alternate current, as at AA′ in Fig. 264, and it continues to be driven, though the impulse is now only oscillatory.

CHAPTER XI

ELECTRO-CHEMISTRY

Lesson XLVII. — *Electrolysis*

487. Electromotive-force of Polarization. ple laws of definite chemical action due to having been laid down in Lesson XIX. it consider the relations between the chemical its electrical equivalent. Whenever an el decomposed by a current, the resolved ions dency to reunite, that tendency being comm "chemical affinity." Thus when zinc sulphat split up into Zn and SO_4 the zinc tends to di into the solution, and so spread the potentia the system. But zinc dissolving into sulphu up an electromotive-force of definite amount; the zinc away from the sulphuric acid require motive-force at least as great as this, and in direction to it. So, again, when acidulat decomposed in a voltameter, the separated hy oxygen tend to reunite and set up an oppos motive-force of no less than 1·47 volts. Th electromotive-force, which is in fact the meas "chemical affinity," is termed the electromo polarization. It can be observed in any wate (Art. 243) by simply disconnecting the wir battery and joining them to a galvanomet

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then QzH represents the value (in heat units) of chemical work done by the flow of the Q units; and value can immediately be translated into *ergs* of worl multiplying by Joule's equivalent J ($= 42 \times 10^6$). Table on page 512.]

We have therefore the following equality:—

$$EQ = QzHJ; \text{ whence it follows that}$$

$E = zHJ$; or, in words, *the electromotive-force of chemical reaction is equal to the product of the electro-chen equivalent of the separated ion into its heat of combination pressed in dynamical units.*

*Examples.** — (1) *Electromotive-force of* **Hydrogen** *tend to unite with Oxygen.* For Hydrogen $z = \cdot0001038$ (heat of combination of one gramme) $= 34000$ gram degree-units; $J = 42 \times 10^6$.

$\cdot0001038 \times 34000 \times 42 \times 10^6 = 1\cdot48 \times 10^8$ "absol units of electromotive-force, or $= 1\cdot48$ *volts.*

(2) *Electromotive-force of* **Zinc** *dissolving into Sulph Acid.* $z = \cdot00337$; $H = 1670$ (according to Julius Th sen); $J = 42 \times 10^6$.

$$\cdot00337 \times 1670 \times 42 \times 10^6 = 2\cdot364 \times 10^8,$$
$$\text{or} = 2\cdot364 \textit{ volts.}$$

(3) *Electromotive-force of* **Copper** *dissolving into Sulph Acid.* $z = \cdot00327$; $H = 909\cdot5$; $J = 42 \times 10^6$.

$$\cdot00327 \times 909\cdot5 \times 42 \times 10^6 = 1\cdot249 \times 10^8,$$
$$\text{or} = 1\cdot249 \textit{ volts.}$$

(4) *Electromotive-force of a* **Daniell's Cell.** Here zin dissolved at one pole to form zinc sulphate, the ch cal action setting up a + electromotive-force, whil the other pole copper is deposited by the current out

* The figures given in these examples as well as those on p. 51 the heat of combination must be taken as only approximate. The he combination is different at different temperatures, and the heat ev by the salt dissolving in water must also be taken into account. I figures have not yet been ascertained. In fact Von Helmholtz sh that the expression zHJ is incomplete, and that to it should be add term $\theta \cdot dE/d\theta$, wherein θ is the absolute temperature of the cell.

solution of copper sulphate, thereby setting up an opposing (or −) electromotive-force. That due to zinc is shown above to be + 2·364 *volts*, that to deposited copper to be − 1·249. Hence the net electromotive-force of the cell is (neglecting the slight electromotive-force where the two solutions touch) 2·364 − 1·249 = 1·115 *volts*. This is nearly what is found (Art. 181) in practice to be the case. It is less than will suffice to electrolyze water, though two Daniell's cells in series electrolyze water easily.

Since 1 horse-power-hour = 746 watt-hours = 746 ampere-hours at 1 volt, it follows that at V volts the number of ampere-hours will = 746 ÷ V. Now as the weight of zinc consumed in a cell is 1·213 grammes per ampere-hour (when there is no waste) the consumption will be as follows: —

$$\left.\begin{array}{l}\text{Weight of zinc used}\\ \text{per horse-power-hour}\end{array}\right\} = \frac{746}{V} \times 1{\cdot}213 \text{ grm.} = \frac{2}{V}\text{ lbs.}$$

Hence the quantity of zinc that must be consumed to generate 1 horse-power-hour in any battery of cells cannot be less than 2 lbs. ÷ the available volts of a single cell of the battery.

Example. — If a new cell can be invented to give 2 volts at its terminals when in full work, a battery of such cells, however arranged, will consume 1 lb. of zinc per hour per horse-power, or 1·34 lbs. per "unit" of supply (or kilowatt-hour).

An equivalent quantity of exciting and depolarizing chemicals will also be used, and these will increase the total cost per unit. It is clear that as a source of public supply primary batteries consuming zinc can never compete in price with dynamos driven by steam. The actual cost of coal to central stations in London is from 1 to 1¼ pence per "unit"; and the maximum legal price that a supply company may charge in Great Britain for electric energy is eightpence per "unit" (see Art. 440).

489. Electro-Chemical Power of Metals. — The accompanying Table gives the electromotive-force of the

different metals as calculated (Art. 488) from the heat evolved by the combination with oxygen of a portion of the metal equivalent electro-chemically in amount to one gramme of hydrogen. The figures in the second column are in calories. The figures in the third column are calculated from these in the second by multiplying by the electro-chemical equivalent of hydrogen, and by Joule's equivalent (42×10^6) and dividing by 10^8, to reduce to volts. The electromotive-forces as observed (in dilute sulphuric acid) are added for comparison.

Substance.	Heat of Oxidation of Equivalent.	E.M.F. calculated.		E.M.F. observed.
		Relatively to Oxygen.	Relatively to Zinc.	
Potassium . . .	69,800	3·01	+1·18	+1·13
Sodium	67,800	2·91	+1·09	
Zinc	42,700	1·83	0·	0·
Iron	34,120	1·55	−0·28	
Hydrogen . . .	34,000	1·47	−0·36	
Lead	25,100	1·12	−0·71	−0·54
Copper	18,760	·80	−1·08	−1·047
Silver	9,000	·39	−1·44	
Platinum . . .	7,500	·33	−1·50	−1·53
Carbon	2,000	·09	−1·74	
Oxygen	0	0·	−1·83	−1·85
(Nitric Acid) . .	− 6,000	−0·26	−2·09	−1·94
(Black Oxide of Manganese) . .	− 6,500	−0·29	−2·12	−2·23
(Peroxide of Lead)	−12,150	−0·52	−2·35	−2·52
(Ozone)	−14,800	−0·63	−2·46	−2·64
(Permanganic Acid)	−25,070	−1·09	−2·92	−3·03

The order in which these metals are arranged is in fact nothing else than the order of oxidizability of the metals (in the presence of dilute sulphuric acid); for that metal tends most to oxidize which can, by oxidizing, give out the most energy. It also shows the order in which

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metals, potassium, sodium, zinc, etc., come last; t oxidizable or "electronegative" metals preceding The order varies with the nature, strength, and te ture of the solution used.

(*e.*) From a solution of mixed metallic salts tl electropositive metal is not deposited first, if the (is so strong relatively to the size of the kathod impoverish the solution in its neighbourhood. To (alloys a solution must be found in which both tend to dissolve with equal electromotive-forces.

(*f.*) The liberated ions appear only at the elec

(*g.*) For each electrolyte a *minimum electromoti* is requisite, without which complete electrolysis cat effected. (See Art. 491.)

(*h.*) If the current be of less electromotive-forc the requisite minimum, electrolysis may begin, feeble current flow at first, but no ions will be lib the current being completely stopped as soon opposing electromotive-force of polarization has r equality with that of the electrolyzing current.

(*i.*) There is no opposing electromotive-force of ization when electrolysis is effected from a diss anode of the same metal that is being deposited kathode. The feeblest cell will suffice to deposit from sulphate of copper if the anode be a copper p

(*j.*) Where the ions are gases, pressure affec conditions but slightly. Under 300 atmosphere ulated water is still electrolyzed; but in certain (layer of acid so dense as not to conduct collects anode and stops the current.

(*k.*) The chemical work done by a current electrolytic cell is proportional to the *minimum* e motive-force of polarization.

(*l.*) Although the electromotive-force of polar may exceed this minimum, the work done by the c in overcoming this surplus electromotive-force w appear as chemical work, for no more of the ion

liberated; but it will appear as an additional quantity of heat (or "local heat") developed in the electrolytic cell.

(*m.*) Ohm's law holds good for electrolytic conduction.

(*n.*) Amongst the secondary actions which may occur the following are the chief:—

(1) The ions may themselves decompose; as SO_4 into $SO_3 + O$. (2) The ions may react on the electrodes; as when acidulated water is electrolyzed between zinc electrodes, no oxygen being liberated, owing to the affinity of zinc for oxygen. (3) The ions may be liberated in an abnormal state. Thus oxygen is frequently liberated in its allotropic condition as ozone, particularly when permanganates are electrolyzed. The "nascent" hydrogen liberated by the electrolysis of dilute acid has peculiarly active chemical properties. So also the metals are sometimes deposited abnormally: copper in a black pulverulent film; antimony in roundish gray masses (from the terchloride solution) which possess a curious explosive property. When a solution of lead is electrolyzed a film of peroxide of lead forms *upon the anode*. If this be a plate of polished metal placed horizontally in the liquid beneath a platinum wire as a kathode, the deposit takes place in symmetrical rings of varying thickness, the thickest deposit being at the centre. These rings, known as Nobili's rings, exhibit all the tints of the rainbow, owing to interference of the waves of light occurring in the film. The colours form, in fact, in reversed order, the "colours of thin plates" of Newton's rings.

491. Hypotheses of Grotthuss and of Clausius.—A complete theory of electrolysis must explain—*firstly*, the transfer of electricity, and *secondly*, the transfer of matter, through the liquid of the cell. The latter point is the one to which most attention has been given, since the "migration of the ions" (*i.e.* their transfer through the liquid) in two opposite directions, and their appearance at the electrodes *only*, are salient facts.

The hypothesis put forward in 1805 by Grotthuss serves fairly, when stated in accordance with modern terms, to explain these facts. Grotthuss supposes that, when two metal plates at different potentials are placed

in a cell, the first effect produced in the liquid is that the molecules of the liquid arrange themselves in innumerable chains, in which every molecule has its constituent atoms pointing in a certain direction; the atom of electropositive substance being attracted toward the kathode, and the fellow atom of electronegative substance being attracted toward the anode. (This assumes that the constituent atoms grouped in the molecule retain their individual electric properties.) The diagram of Fig. 266 shows, in the case of hydrochloric

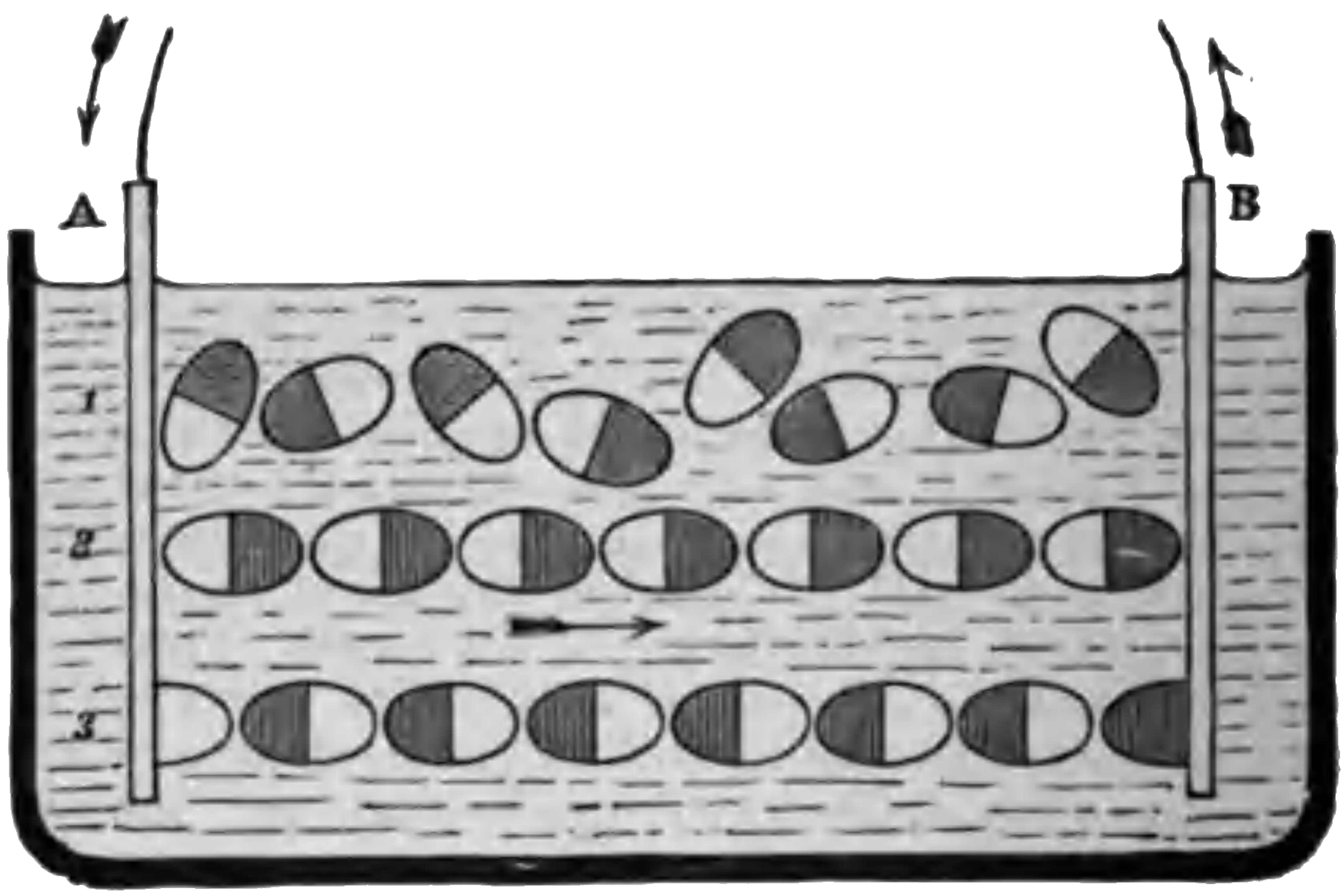


Fig. 266.

acid, a first row of molecules distributed at random, and secondly grouped in a chain as described. The action which Grotthuss then supposes to take place is that an interchange of partners goes on between the separate atoms all along the line, each H atom uniting with the Cl atom belonging to the neighbouring molecule, a + half molecule of hydrogen being liberated at the kathode, and a − half molecule of chlorine at the anode. This action would leave the molecules as in the third row, and would, when repeated, result in a double migration of hydrogen atoms in one direction and of chlorine atoms

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Lesson XLVIII. — *Accumulators*

492. Accumulators or Secondary Batteries. — A voltameter, or series of voltameters, whose electrodes are thus charged respectively with hydrogen and oxygen, will serve as *secondary batteries*, in which the energy of a current may be stored up and again given out. Ritter, who in 1803 constructed a secondary pile, used electrodes of platinum. It will be seen that such cells do not accumulate or store electricity; what they accumulate is energy, which they store in the form of chemical work. A secondary cell resembles a Leyden jar in that it can be charged and then discharged. The residual charges of Leyden jars, though small in quantity and transient in their discharge, yet exactly resemble the polarization-charges of voltameters. Varley found 1 sq. centim. of platinum foil in dilute acid to act as a condenser of about 63 microfarads capacity, when polarized to a potential-difference of 1 volt. Gaston Planté, in 1860, devised a secondary cell consisting of two pieces of sheet lead rolled up (without actual contact) as electrodes, dipping into dilute sulphuric acid, as in Fig. 267. To "form" or prepare the lead it was charged with currents which after a time were reversed in direction, and after a further time again reversed until, after several reversals, it became coated with a semi-porous film of brown dioxide of lead

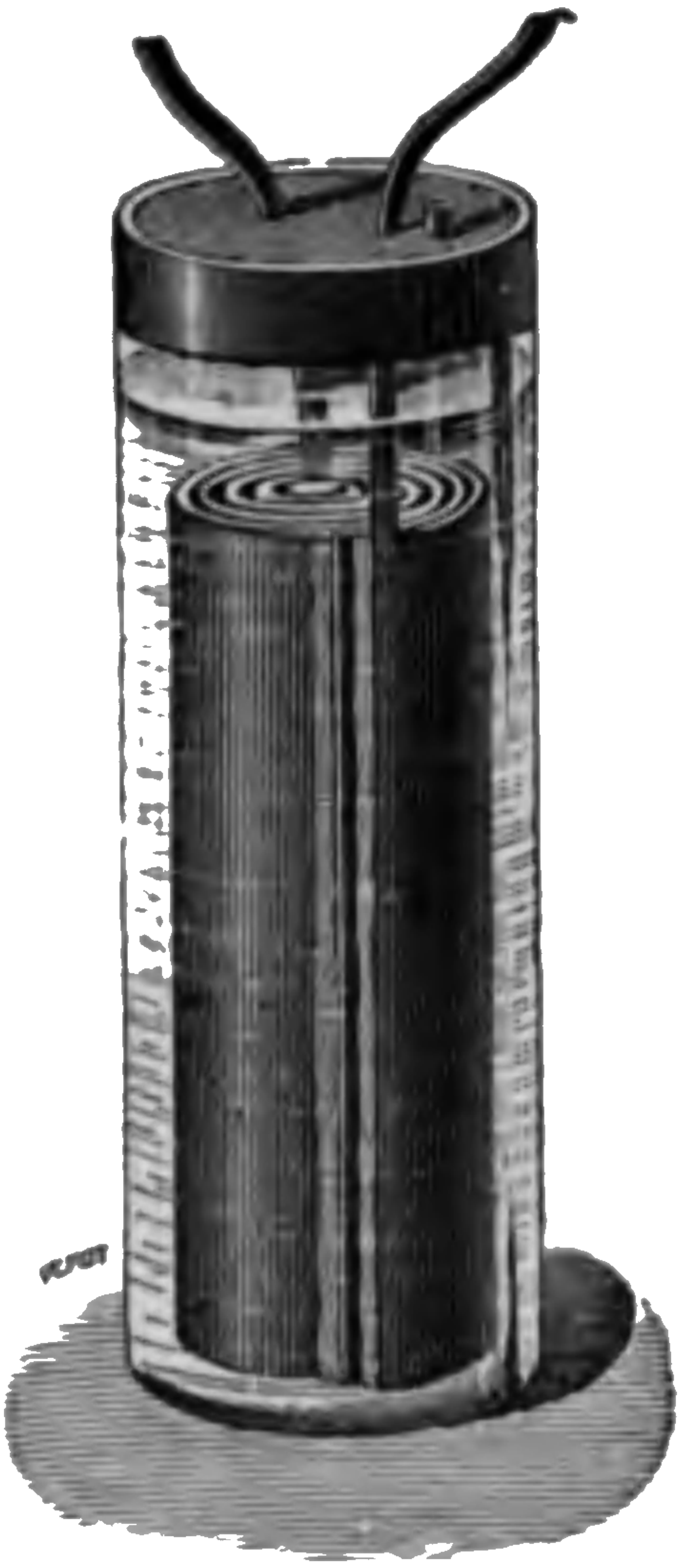


Fig. 267.

on the anode plate; the kathode plate assuming a spongy metallic state presenting a large amount of surface of high chemical activity. When such a secondary battery, or *accumulator*, is charged by connecting it with a dynamo (shunt-wound), or other powerful generator of currents, the anode plate becomes peroxidized, while the kathode plate is deoxidized by the hydrogen that is liberated. The plates may remain for many days in this condition, and will furnish a current until the two lead surfaces are reduced to a chemically inactive state. The electromotive-force of such cells is from 2·0 to 1·85 volts during discharge. Planté ingeniously arranged batteries of such cells so that they can be charged in parallel, and discharged in series, giving (for a short time) strong currents at extremely high voltages. Faure, in 1881, modified the Planté accumulator by giving the two lead plates a preliminary coating of *red-lead* (or minium). When a current is passed through the cell to charge it, the red-lead is peroxidized at the anode, and reduced,—first to a condition of lower oxide, then to the spongy metallic state,—at the kathode, and thus a greater thickness of the working substance is provided, and takes far less time to "form" than is the case in Planté's cells. In modern accumulators the red-lead (or litharge), freshly mixed with dilute sulphuric acid to the form of a paste, is pressed into the holes of a leaden grid, shaped so as to give it a good mechanical attachment. During the subsequent process of "formation" the hardened paste is reduced on one plate and peroxidized on the other. A cell of the

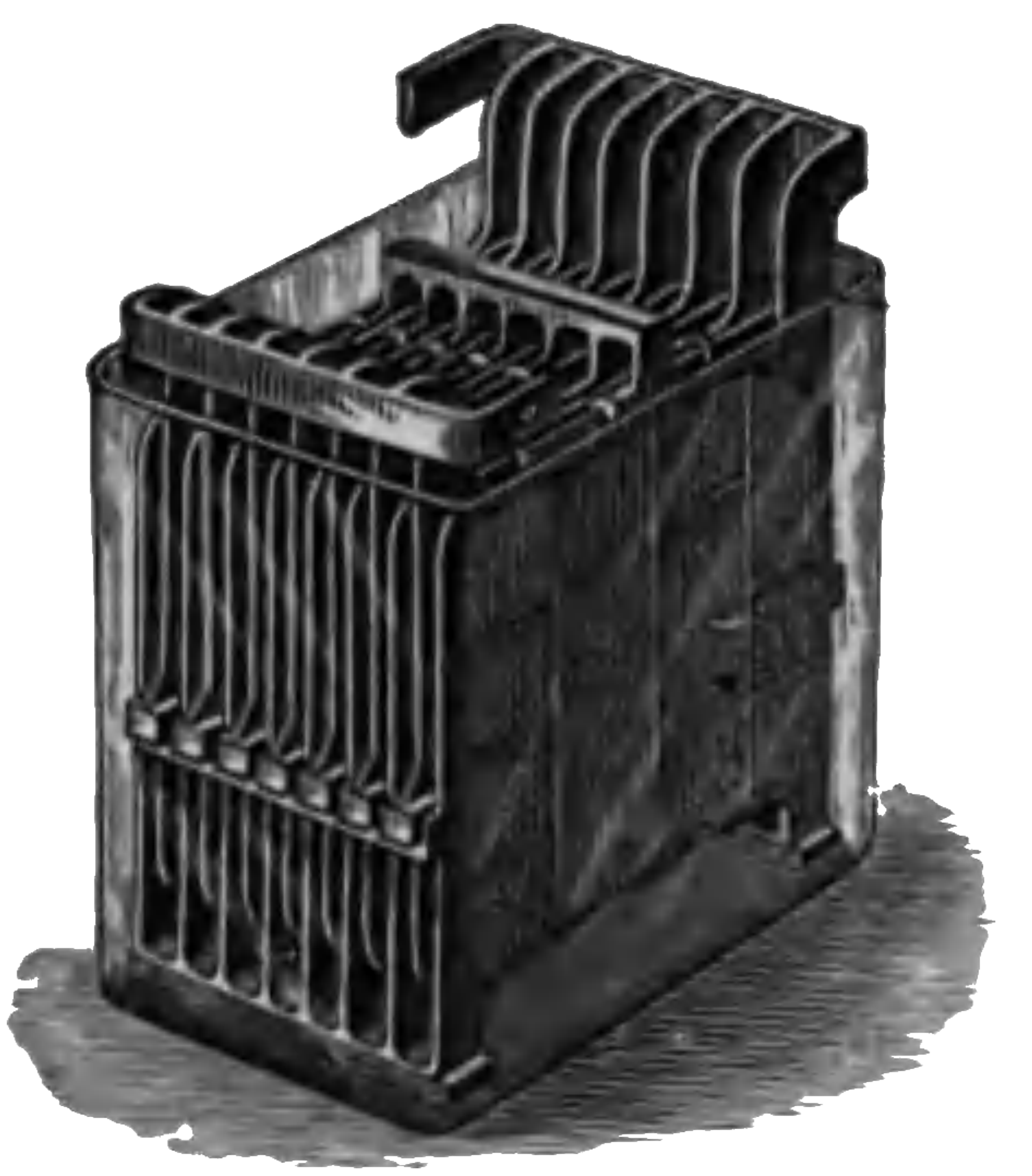


Fig. 268.

kind known as the E.P.S. cell is shown in Fig. 268. Accumulators are still made on the Planté method from metallic lead, which is first finely divided on its surface by some mechanical or chemical means, and then "formed" by prolonged charging. Cells of this type are not so subject to disintegration as paste cells, and may be discharged at a greater rate. To keep accumulators in good condition they should be charged up every day till full (known by bubbles rising) and not be discharged too quickly. The density of acid should never be allowed to exceed 1·21 nor fall below 1·15.

493. Grove's Gas Battery.—Sir W. Grove devised a cell in which platinum electrodes, in contact respectively with hydrogen and oxygen gas, replaced the usual zinc and copper plates. Each of these gases is partially occluded by the metal platinum, which, when so treated, behaves like a different metal.

Attempts have been made to generate electricity on a larger scale by means of gas batteries. Mond and Langer found that the greatest E.M.F. to be obtained from a cell of hydrogen and oxygen, with finely divided platinum as collectors, was 0·97, the difference between this and the theoretical, 1·47, being lost in heat generated by the condensation of the gases by the platinum.

LESSON XLIX.—*Electrodeposition*

494. Electrometallurgy.—The applications of electrochemistry to the industries are threefold. *Firstly*, to the reduction of metals from solutions of their ores, the process is useful in the accurate assay of certain ores, as, for example, of copper; *secondly*, to the copying of types, plaster casts, and metal-work by kathode deposits of metal; *thirdly*, to the covering of objects made of baser metal with a thin film of another metal, such as gold, silver, or nickel. All these operations are included under the general term of *electrometallurgy*.

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Electrotypes of copper are easily made by hanging a suitable mould in a cell containing a nearly saturated and slightly acidulated solution of sulphate of copper, and passing a current of a battery through the cell, the mould metallized on its surface being the kathode, a plate of copper being employed as an anode, dissolving gradually into the liquid at a rate exactly equal to the rate of deposition at the kathode. This use of a separate cell or "bath" is more convenient than producing the electrotypes in the actual cell of a Daniell's battery. The process is largely employed at the present day to reproduce repoussé and chased ornament and other works of art in facsimile, and to multiply copies of wood blocks for printing. Almost all the illustrations in this book, for example, are printed from electrotype copies, and not from the original wood blocks, which would not wear so well. In all deposition processes success largely depends on having the proper current-density. To deposit metals that are more positive than hydrogen, such as zinc or chromium, it is advisable to use concentrated solutions and high current-densities. For metals that are less positive, such as copper and silver, the current-density may be less. To procure a good tough deposit of copper the current should not exceed 15 amperes per square foot of kathode surface. If a more rapid deposit is required, a solution of nitrate of copper should be used and kept in rapid agitation.

To deposit iron (by the process known as *acierage*, or *steel-facing*) a very large sheet of iron is used as anode, and the liquid used is simply a solution of sal ammoniac in water. This solution is "charged" with iron by passing the current for a little time through the bath prior to inserting the object to be steel-faced.

496. Electroplating.—In 1801 Wollaston observed that a piece of silver, connected with a more positive metal, became coated with copper when put into a solution of copper. In 1805 Brugnatelli gilded two silver

medals by making them the kathodes of a cell containing a solution of gold. Messrs. Elkington, about the year 1840, introduced the commercial processes of electroplating. In these processes a baser metal, such as German silver (an alloy of zinc, copper, and nickel), is covered with a thin film of silver or gold, the solutions employed being, for *electro-gilding*, the double cyanide of gold and potassium, and for *electro-silvering* the double cyanide of silver and potassium.

Fig. 269 shows a battery and a plating-vat containing the silver solution. As anode is hung a plate of metallic

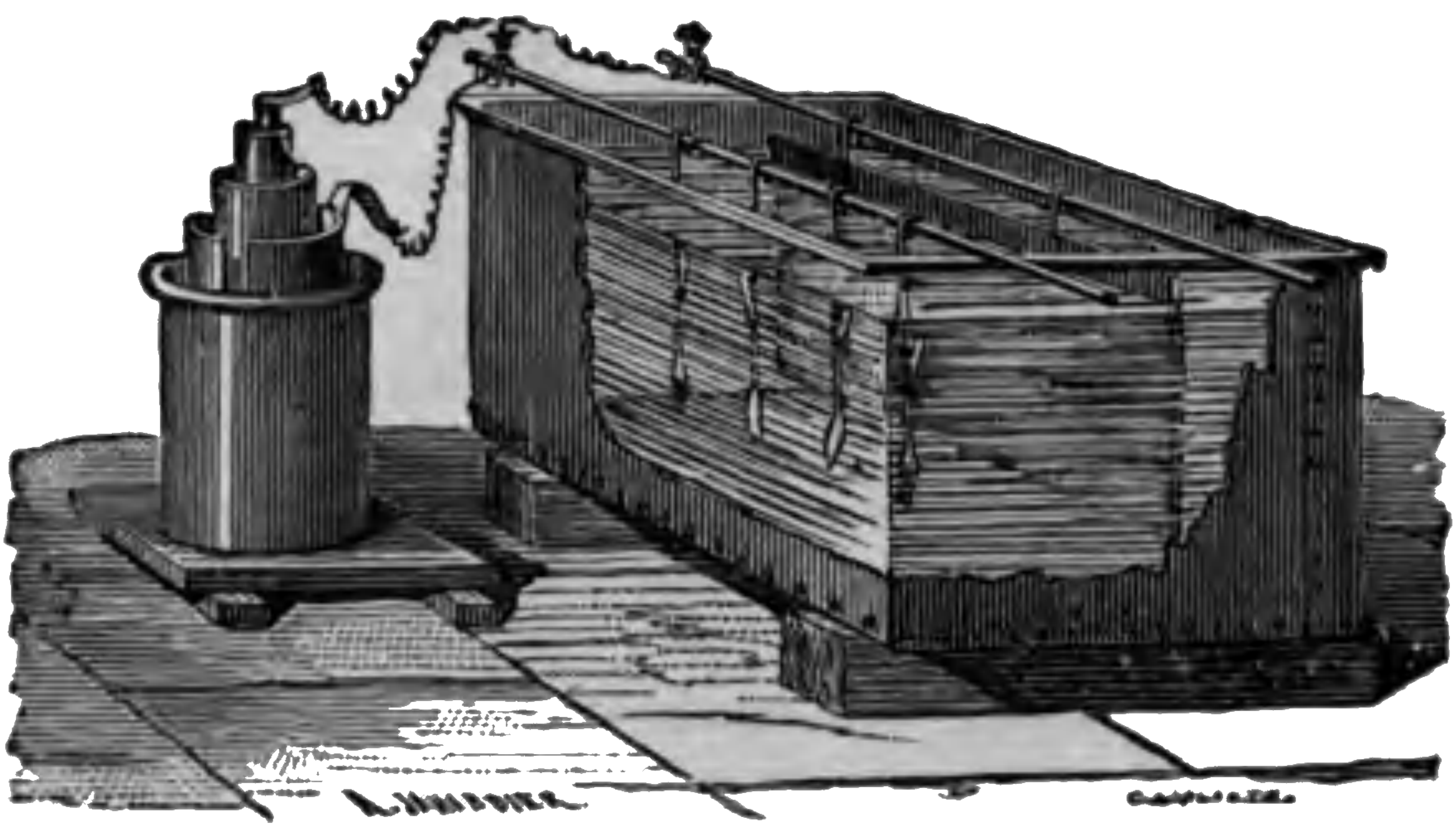


Fig. 269.

silver which dissolves into the liquid. To the kathode are suspended the spoons, forks, or other articles which are to receive a coating of silver. The addition of a minute trace of bisulphide of carbon to the solution causes the deposited metal to have a bright surface. If the current is too strong, and the deposition too rapid, the deposited metal is grayish and crystalline.

In gilding base metals, such as pewter, they are usually first copper-coated. The gilding of the insides of jugs and cups is effected by filling the jug or cup with the gilding solution, and suspending in it an anode of gold,

the vessel itself being connected to the – pole of the battery.

In silvering or gilding objects of iron it is usual first to plate them with a thin coating of copper deposited from an "alkaline" copper bath containing an ammoniacal solution of cyanide of copper. Brass is deposited also from an ammoniacal solution of the mixed cyanides of copper and zinc. In the deposition of nickel a solution of the double sulphate of nickel and ammonium is used; the anode being a sheet of rolled (or cast) nickel.

Except on the very small scale batteries are now seldom used for electrotyping and plating. A shunt-wound dynamo designed to give a large output of current at 5 to 10 volts pressure is generally preferred.

496a. Other Electrolytic Processes.—The electrolytic action of the current is now commercially employed for other purposes than the deposition of metals. By the electrolysis of chloride of potassium under suitable conditions chlorate of potash is now manufactured in large quantities. Bleaching liquors containing hypochlorites can also be produced from chlorides. Caustic soda is prepared by electrolysis of common salt; and several electrolytic methods of disinfecting sewage have been proposed.

It has also been shown that the slow processes of tanning can be accelerated by the aid of electric currents, the action being probably osmotic rather than electrolytic.

It seems probable that in the future the use of electric currents will enter largely into the chemical manufactures.

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producing audible sounds according to a ce
Morse (New York, 1837) devised a telegrap
the attraction of an armature by an electron
made to mark a dot or a dash upon a movi
paper. Steinheil (Munich, 1837) discovered t
of a return-wire the *earth* might be used, co
made to earth at the two ends by means of
(see Fig. 274) sunk in the ground. Gintl
Stearns (New York, 1870) devised methods
signalling. Stark (Vienna) and Bosscha (Le
invented *diplex* signalling, and Heaviside (Lo
and Edison (Newark, N. J., 1874) invented
telegraphy. Varley (London, 1870) and E
(Chicago, 1874) devised *harmonic* telegraphs.
speed work Wheatstone devised his automatic t
in which the signs which represent the lette
punched by machinery on strips of paper; th
run at a great speed through the transmitting
which telegraphs them off at a much greater
the separate signals were telegraphed by han
devised a type-printing telegraph. Wheatsto
an ABC telegraph in which signals are spelled
which moves over a dial. Cowper (1876)
Gray (1893) invented autographic writing
For cable-working Lord Kelvin invented
galvanometer and his delicate siphon-recor
impossible in these Lessons to describe more t
two of the simple ordinary forms of telegraph
now in use in Great Britain. For further i
consult Prescott's Electricity and the Electric
or for British telegraphs, the manuals of C
Preece and Sivewright.

498. Single-Needle Instrument. — The si
instrument (Fig. 270) consists essentially of
galvanometer, in which a lightly hung magn
is deflected to right or left when a current
one direction or the other, around a coil s

the needle; the needle visible in front of the dial is but an index, the real magnetic needle being behind. A code of movements agreed upon comprises the whole alphabet in combinations of motions to right or left. In order to send currents in either direction through the circuit, a "signalling key" or "tapper" is usually employed. The tapper at one end of the line works the instrument at the other; but for the sake of convenience it is fixed to the receiving instrument. In Fig. 270 the two protruding levers at the base form the tapper, and by depressing the right hand one or the left hand one, currents are sent in either direction at will.

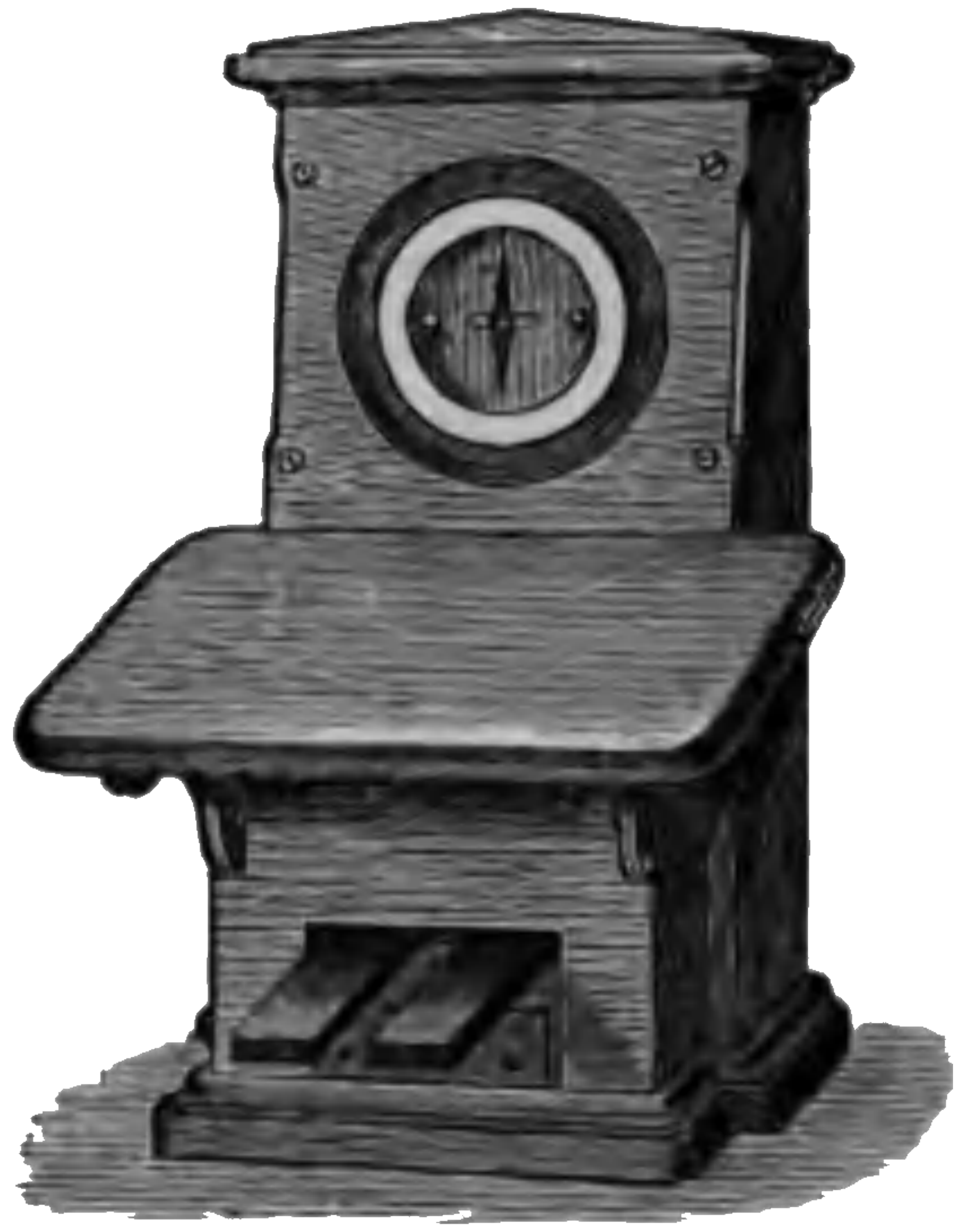


Fig. 270.

The principle of action will be made more clear by

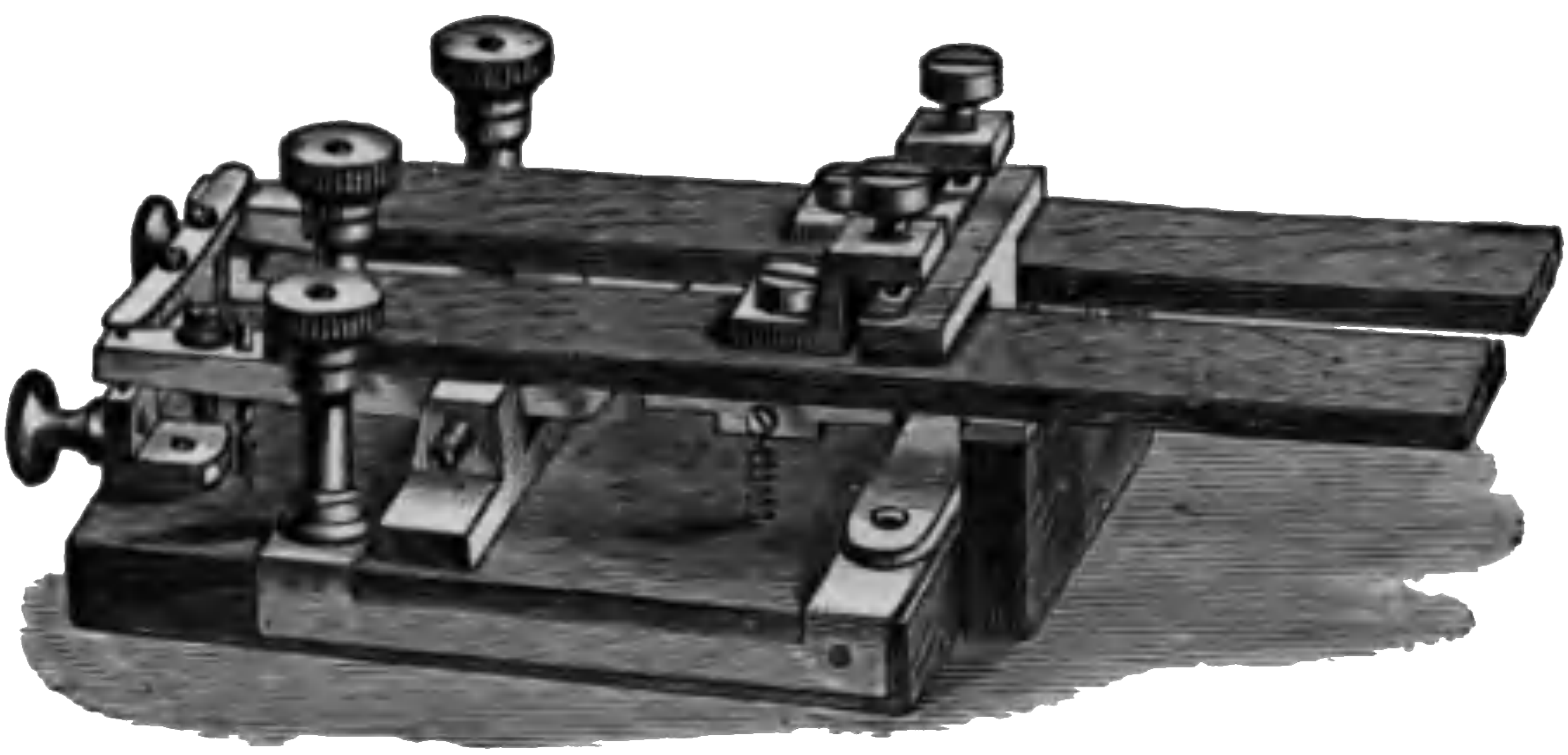


Fig. 271.

reference to Fig. 271, which shows a separate signalling key. The two horizontal levers are respectively in communication with the "line," and with the return-line

through "earth." When not in use both levers spring up against a cross strip of metal joined to the zinc pole of the battery. At their further end is another cross strip, which communicates with the copper (or +) pole of the battery. On depressing the "line" key the current runs through the line and back by earth, or in the *positive* direction. On depressing the "earth" key (the line-key remaining in contact with the zinc-connected strip), the current runs through the earth and back by the line, or in the *negative* direction. Telegraphists ordinarily speak of these as positive and negative *currents* respectively.

499. The Morse Instrument.—The most widely used instrument at the present day is the Morse. It consists essentially of an electromagnet, which, when a current passes through its coils, draws down an armature for a short or a long time. It may either be arranged as a "*sounder*," in which case the operator who is receiving the message listens to the clicks, and notices whether the intervals between them are long or short; or it may be arranged as an "*embosser*," to print dots and dashes upon a strip of paper drawn by clockwork through the instrument. In the most modern form, however, the Morse instrument is arranged as an "*ink-writer*" in which the attraction of the armature downwards lifts a little inky wheel and pushes it against a ribbon of paper.

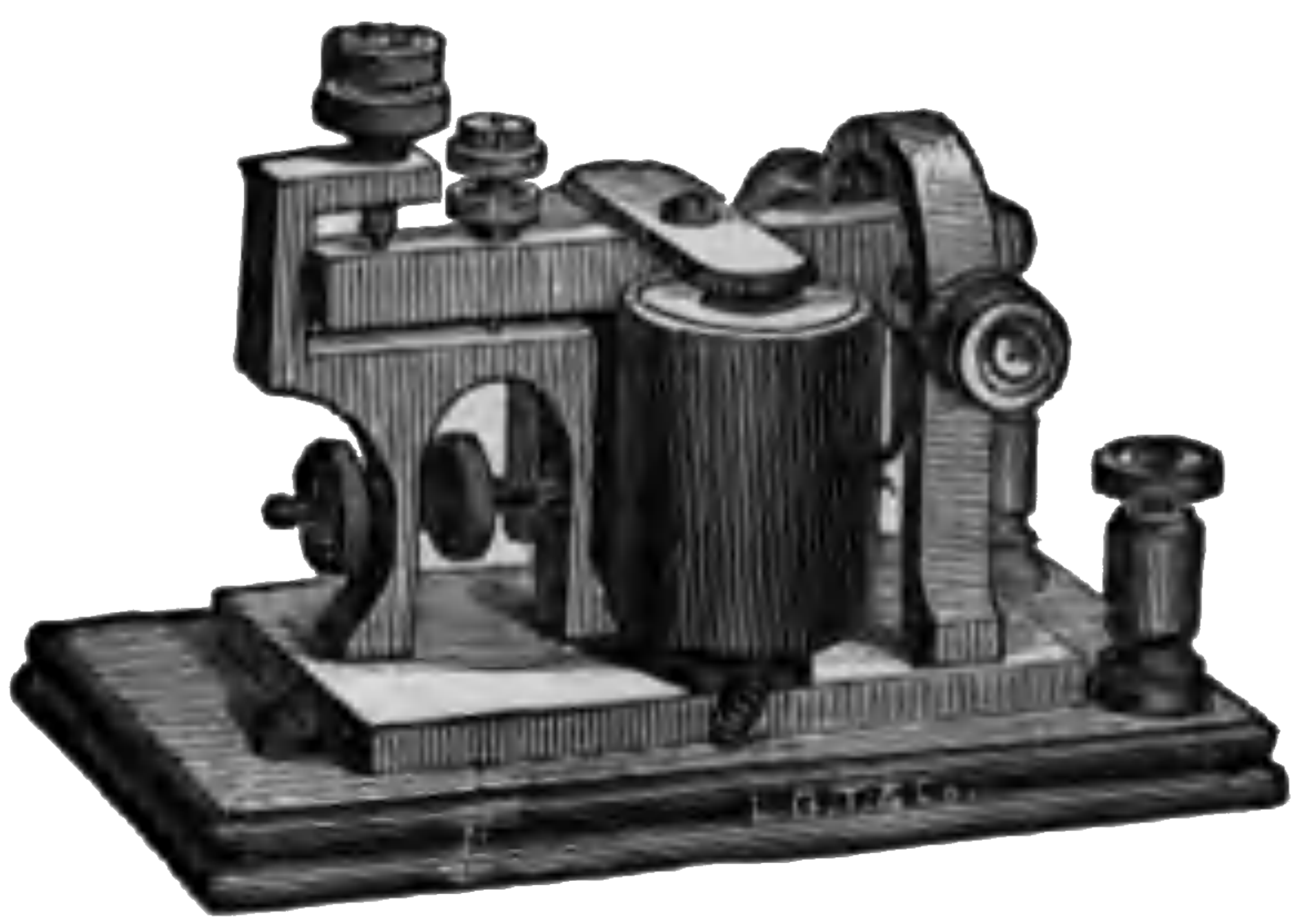


Fig. 272.

The *Morse Sounder*, which is almost universal in the United States, and is being increasingly used in the British Telegraph Service, is depicted in Fig. 272. In

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tary current prints a mere dot; but if the current continues to flow for a longer time while the ribbon of paper moves on, the ink-wheel records a dash. The connexions show how the instrument is worked by a local battery and a relay.

499a. The Morse Alphabets.—The international Morse code, or alphabet of dots and dashes, is as follows:—

A	. —	J	. — — —	S	. . .
B	— . . .	K	— . —	T	—
C	— . — .	L	. — . .	U	. . —
D	— . .	M	— —	V	. . . —
E	.	N	— .	W	. — —
F	. . — .	O	— — —	X	— . . —
G	— — .	P	. — — .	Y	— . — —
H	. . . .	Q	— — . —	Z	— — . .
I	. .	R	. — .		

The American Morse code, originated by Morse himself, is used only in the United States and Canada. It differs in many respects from the International code, the signals for some of the letters depending on the length of the spacings between the dots and dashes; and more than four marks are used to form some of the letters. The marks for H, Y, and Z are four dots, but they are differently spaced. The following is the American Morse code:—

A	. —	M	— —	Y	.
B	— . . .	N	— .	Z	. . . .
C	.	O	.	1	. — — .
D	-	P	. . . . .	2	. . — . .
E	.	Q	. . — .	3	. . . — .
F	. — .	R	. . .	4	. . . . —
G	— — .	S	. . .	5	— — —
H	. . . .	T	-	6	. . . . . .
I	.	U	. . —	7	— — . .
J	-	V	. —	8	— . . . .
K	-		- —	9	— . . —
L			- . .	0	———

499b. The Morse Key. — The key used for operating Morse telegraphs. The American pattern differs somewhat from the European pattern, and the mode of use is not precisely the same.

The general appearance of the American pattern of Morse key is shown in Fig. 274.

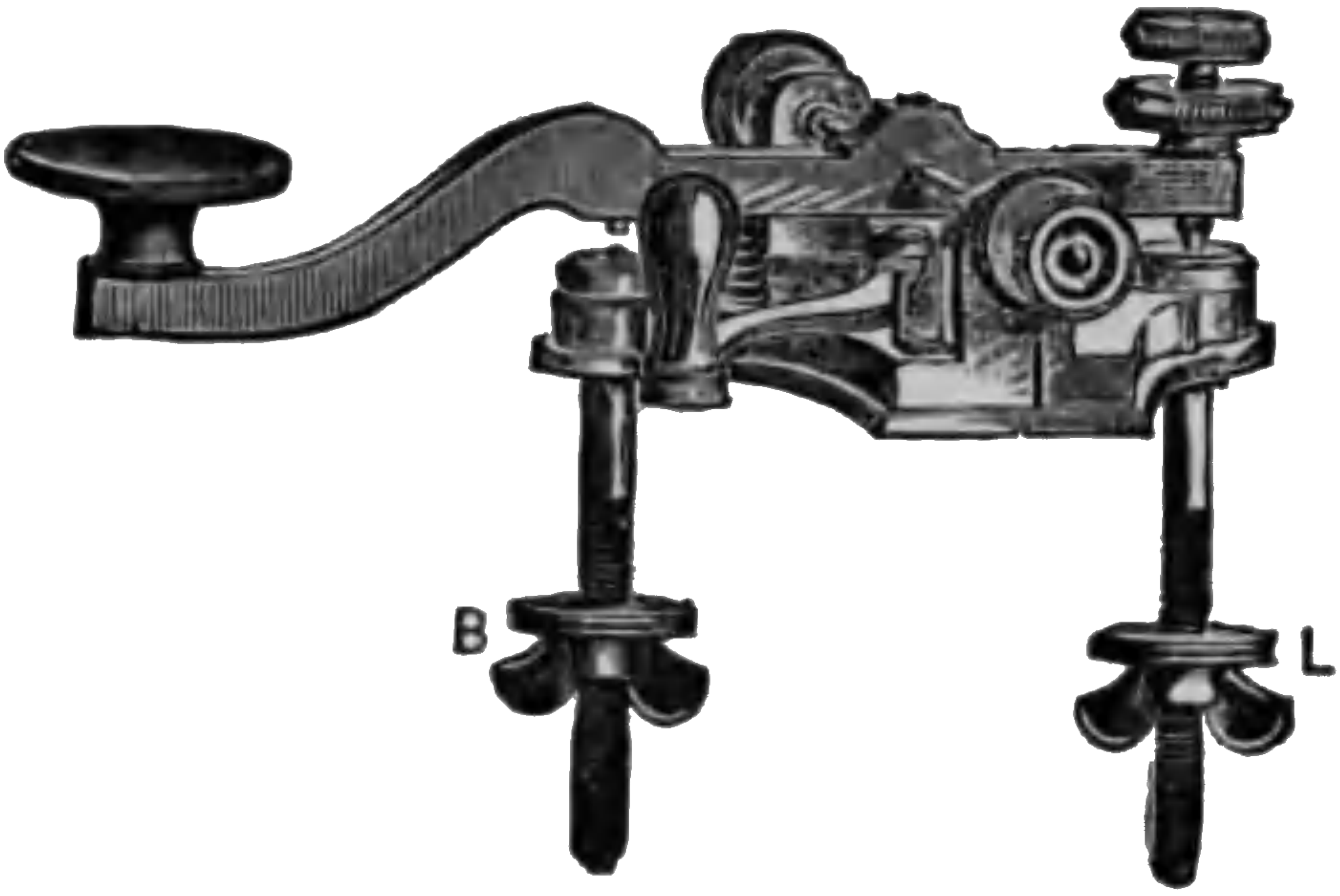


Fig. 274.

The key is fastened to the table by the screws B and L, the former being insulated from the metal base and lever, while L is not insulated. One wire is clamped to the metal of the key at L, the other is clamped to B. The lever, which is provided with a finger-piece, has on its lower side a short platinum pin just above the head of the screw B, so that when the operator depresses the lever it makes contact on the head of the screw and completes the circuit from B to L. The range of motion allowed the lever is regulated by a screw-stop in the further end of the lever. Beside the parts named the key is usually provided with a switch, shown in the Fig. 274 with a small vertical handle. When this is moved to the left it short-circuits the key, and puts B into direct connexion with L. When moved to the right, the circuit is open until such time as the lever is depressed.

The Morse key as used in the British telegraphs is

depicted in Fig. 275. The line wire is connected with the central pivot A. A spring keeps the front end of the key elevated when not in use, so that the line wire is in communication through the rear end of the key with the receiving instrument or relay. Depressing the key breaks this communication, and by putting the line wire in communication with the sending battery transmits a current through the line.

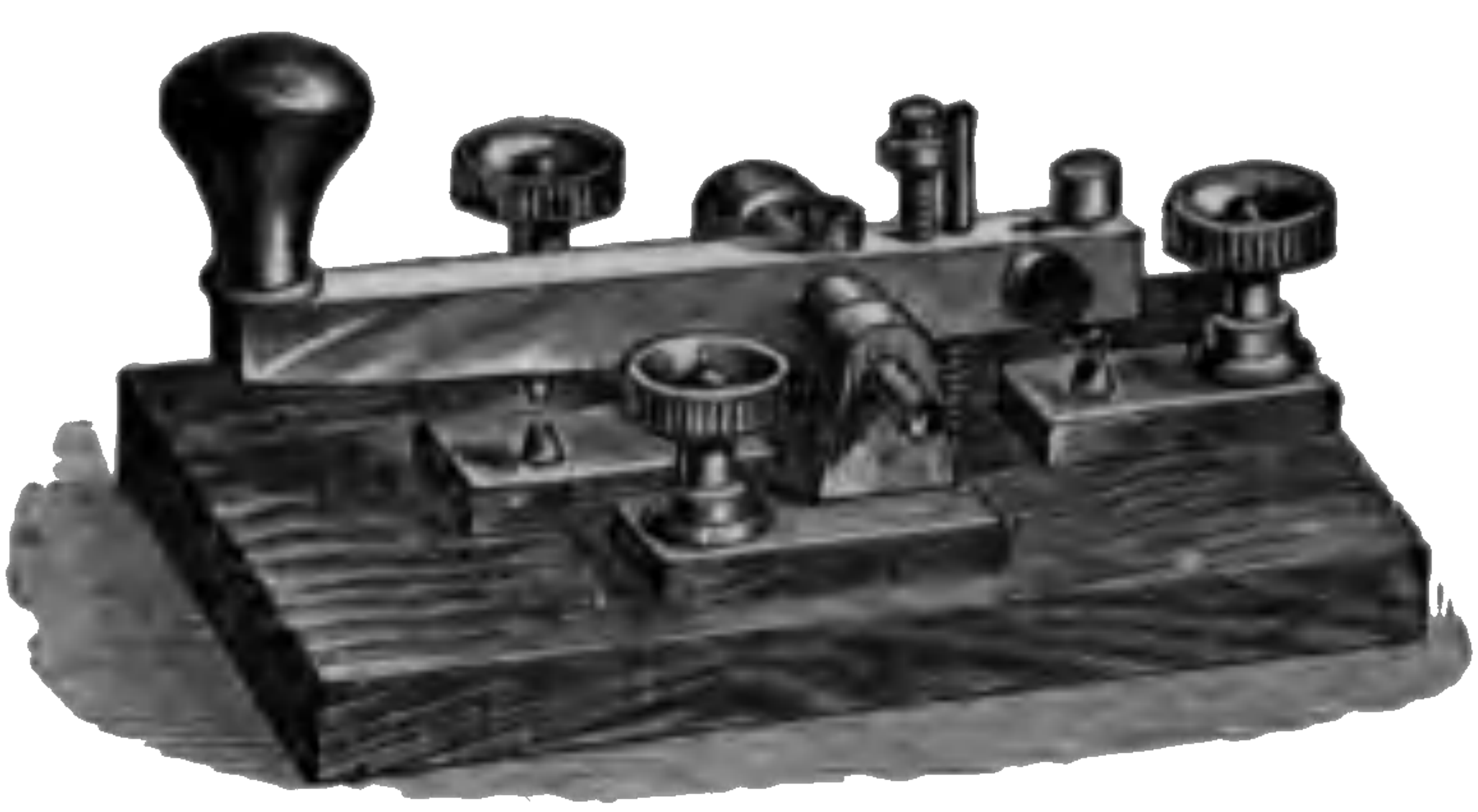


Fig. 275.

500. Open and Closed Circuit Working. — European telegraphs work on the open-circuit plan, the battery being out of circuit when no message is being sent. American telegraphs are usually on the closed-circuit plan, the current being always on until interrupted to send signals. Each plan has its advantages. The closed-circuit plan enables a *way-line* to unite a number of isolated stations all in a single circuit, each one of which can signal to all the rest by opening the circuit. Further, any failure in the line immediately reports itself by the stoppage of the current. The open-circuit plan, which is better suited for communication among dense populations, and for all lines where no instruments are wanted to be inserted at intermediate points, has the advantage of only using the batteries when the telegraph is in actual use.

In the open-circuit plan the key acts, as previously described, merely to open or close the circuit. The general arrangement of apparatus at an intermediate or "way" station is shown in Fig. 276. The current coming along the line enters by the line wire on the right and comes in to the metal base of the key K, where it finds a passage along the switch G (which is closed) to

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its own end. Both ends of the lever must t[h]
furnished with contact-pins of platinum; an[d]
acts as a two-way key. The current flowing t[h]

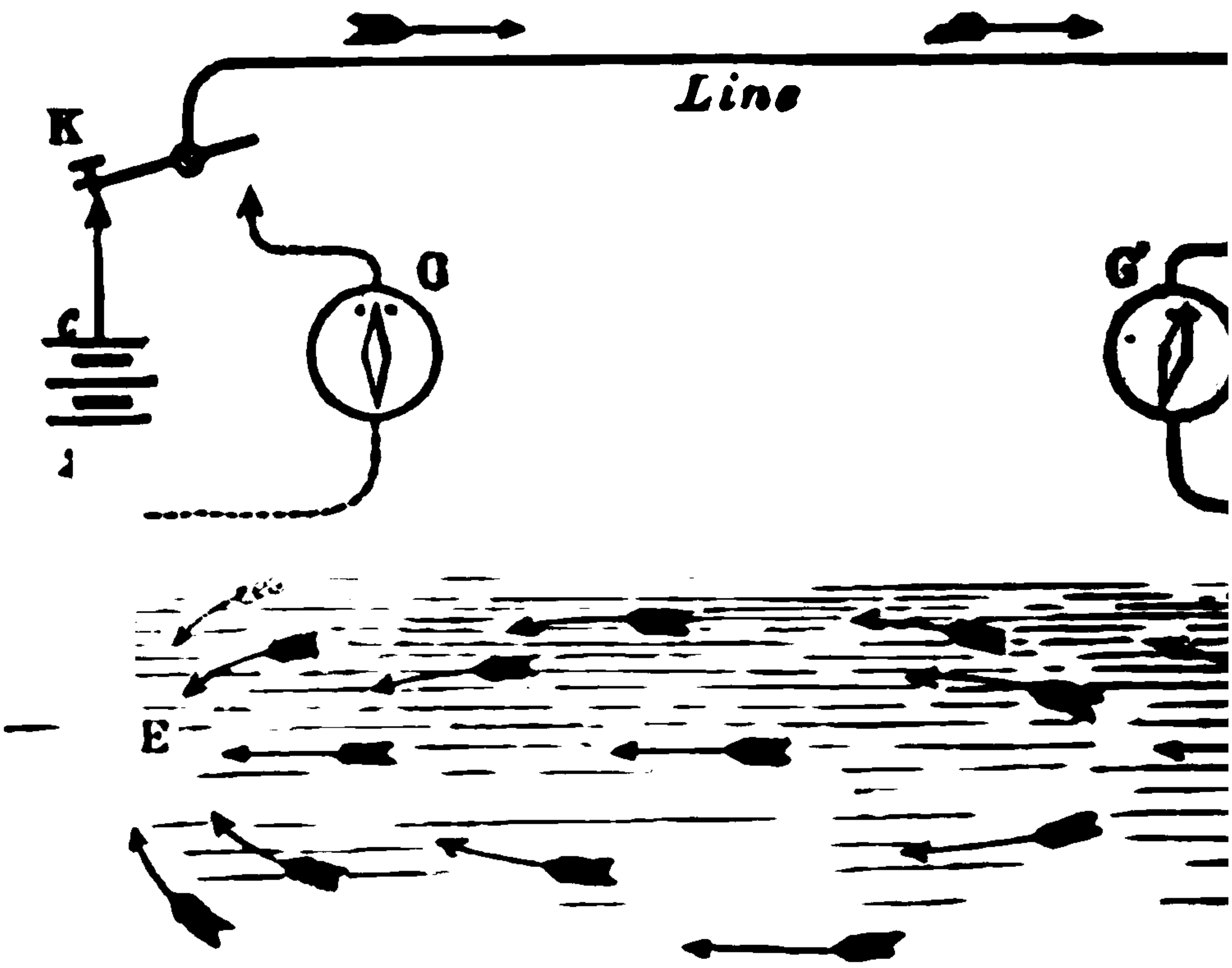


Fig. 277.

line passes through K′ and enters a receiving i
G′ at the distant end, where it produces a s
returns by the earth to the battery whence it s
similar battery and key at the distant end suffi
mit signals in the opposite direction to G whe
depressed. The diagram is drawn as if G we
galvanometer; but the arrangement would pe
the Morse instrument, in which it is only n
either end to send long and short currents with
ing the direction, as with the needle instru
this diagram the battery current is neve
and the method is known as a *single-curren*
There is a so-called *double-current* method of w
which reversing keys (resembling the tapp
271) are used to send after each current in th
direction a second current in the negative direc
double-current method has the advantage o

the signalling to be more rapid on long lines when the retardation due to the static charging of the line is of importance. The second current helps to curb the first and makes the signals shorter and sharper.

501. Relays. — In working over long lines, or where there are a number of instruments on one circuit, the currents are often not strong enough to work the recording instrument directly. In such a case there is interposed a **relay** or **repeater**. This instrument consists of an electromagnet round which the line current flows, and whose delicately poised armature, when attracted, makes contact for a local circuit in which a local battery and the receiving Morse instrument (sounder, or writer) are included. The principle of the relay is, then, that a current too weak to do the work itself may set a strong local current to do its work for it.

In the American plan of working (Fig. 276), the relay is a simple electromagnet having a soft-iron core, and an armature of iron which it attracts whenever a current flows round its coils. It pulls its armature no matter which way the current flows. Such a non-polarized relay of the Western Union pattern is depicted in Fig.

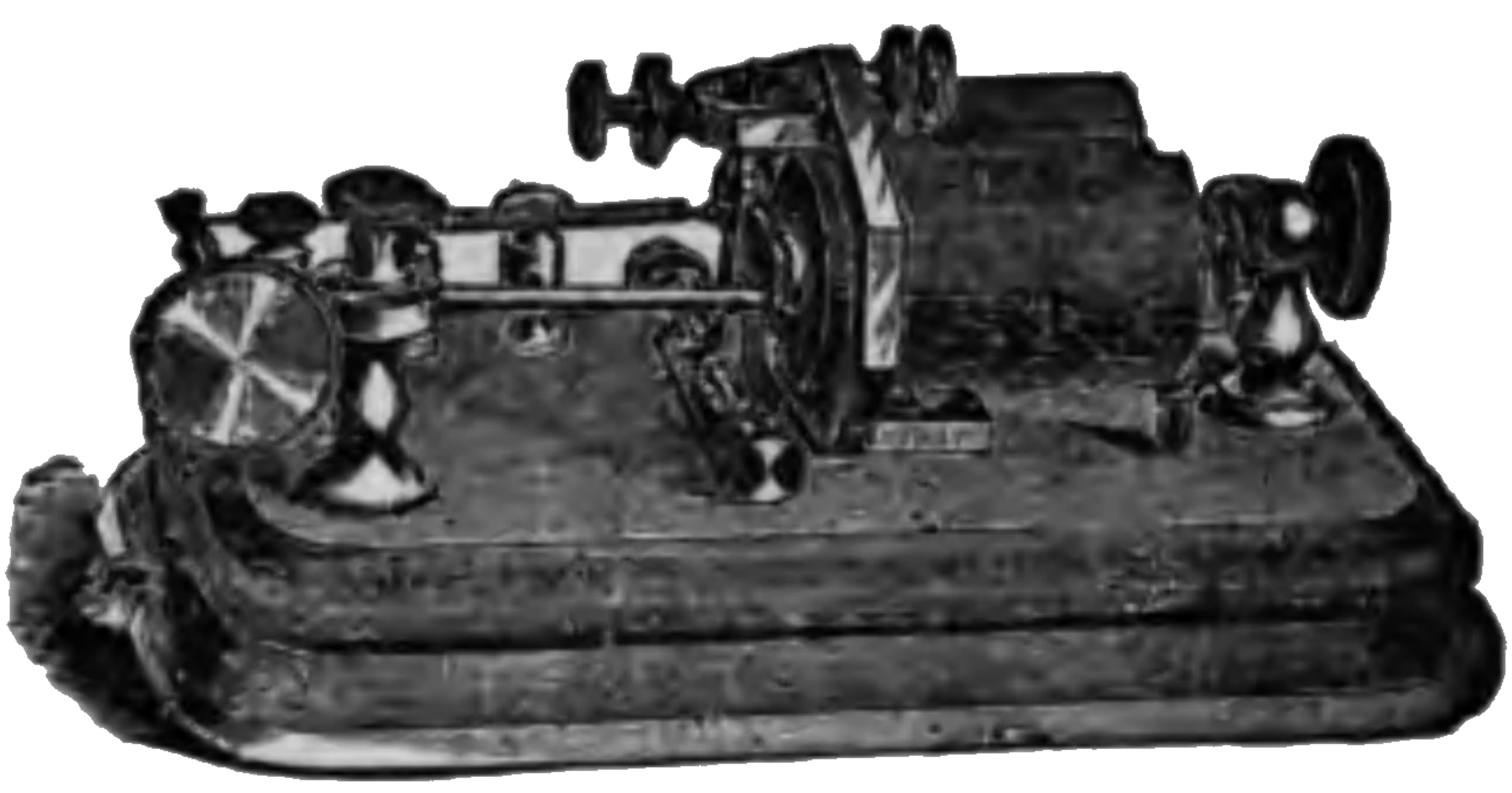


Fig. 278.

278. Its mode of operation is explained by the diagrammatic plan of Fig. 276. Here M is the electromagnet, with its iron armature lightly pivoted at P, and controlled by the spring V. When any current passes, the

light lever or tongue on which the armature turns on its pivot P, and makes contact agains thereby closing a local circuit DXLSYP, wh the sounder S and a local battery L.

In the closed-circuit method of worki duplex telegraphy "polarized relays" are will respond to currents flowing in one dir The polarized relay of Siemens's pattern i diagram in Fig. 279. In it a permanently steel magnet is employed to produce an initial in the cores of the electromagnet, and in lever or tongue. The magnet has its S pole

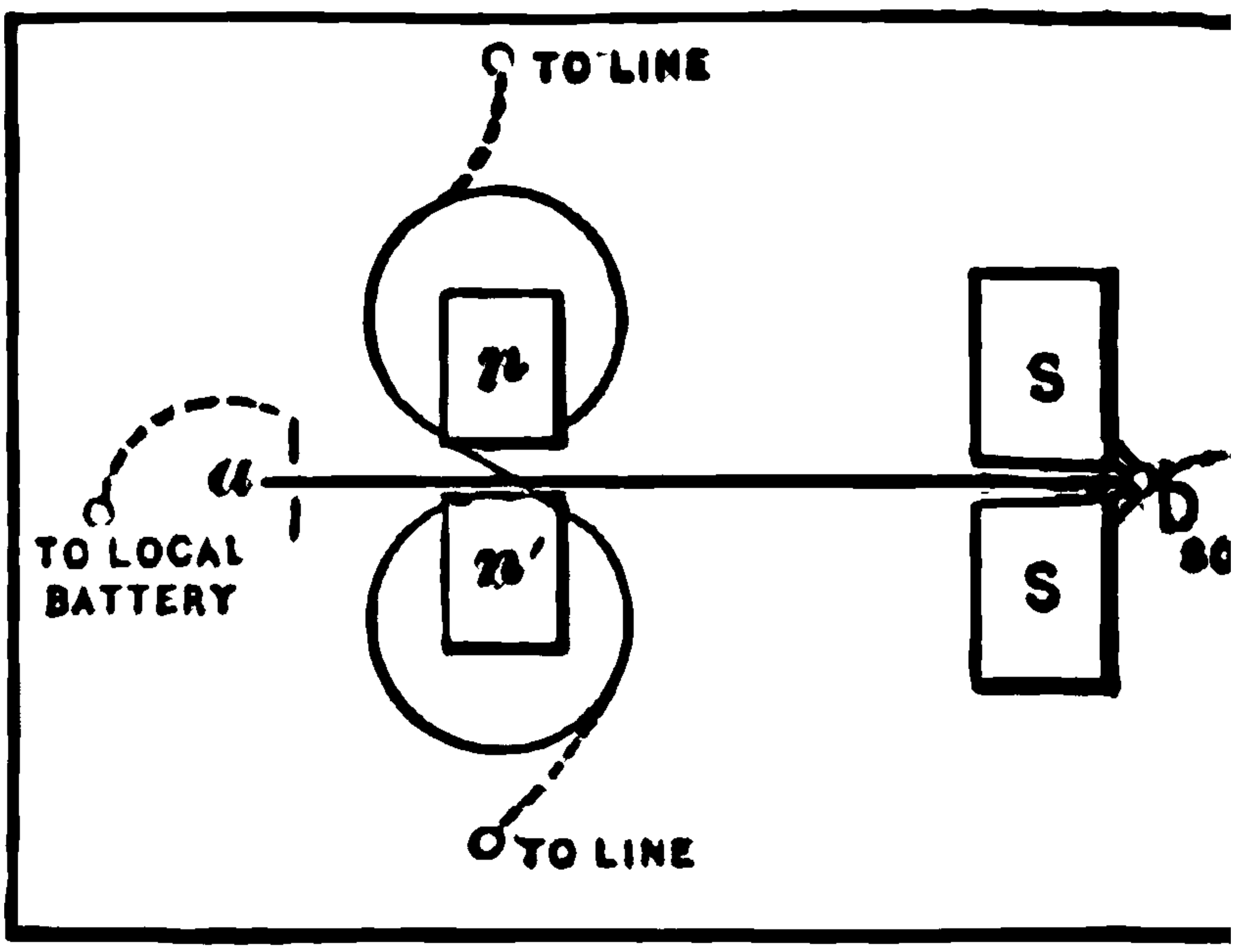


Fig. 279.

right angles and divided so that the tongue relay, which is of iron, may be thereby p given a south polarity. Attached to the N magnet are the two cores, over which the t are slipped, these cores ending in the two marked *n*, *n'*, which are of northern polarity. attract the tongue that lies between them, the pulling more strongly. If now a current circu the coils it will tend to strengthen one of the weaken the other. If it flows in such a dire strengthen *n* and weaken *n'*, the tongue will l

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through the earth before it reaches the distant station, or, as in overhead wires, by two conducting wires touching one another. Various modes for testing the existence and position of faults are known to telegraph engineers; they depend upon accurate measurements of resistance or of capacity. Thus, if a telegraph cable part in mid-ocean it is possible to calculate the distance from the shore end to the broken end by comparing the resistance that the cable is known to offer per mile with the resistance offered by the length up to the fault, and dividing the latter by the former.

503. **Duplex and Quadruplex Telegraphy.** — To send two messages through one wire, one from each end, at the same time, is known as *duplex* working. There are two distinct methods of arranging apparatus for duplex working. The first of these, known as the *differential method*, involves the use of instruments wound with differential coils, and is applicable to special cases. The second method of duplex working, known as the *bridge method*, is capable of much more general application. The diagram of Fig. 281 will explain the general principle. The first requirement in duplex working is that the instrument at each end shall only move in response to signals from the other end, so that an operator at R may be able to signal to the distant instrument M′ without his own instrument M being affected, M being all the while in circuit and able to receive signals from the distant operator at R′. To accomplish this the circuit is divided at R into two branches, which go, by A and B respectively, the one to the line, the other through a certain resistance P to the earth. If the ratio between the resistances in the arms RA and RB is equal to the ratio of the resistances of the line and of P, then, by the principle of Wheatstone's Bridge, *no* current will pass through M. So M does not show any currents sent from R; but M′ will show them, for the current on arriving at C will divide into two parts, part flowing round to the earth by R′, the other

part flowing through M′ and producing a signal. If, while this is going on, the operator at the distant R′ depresses his key and sends an equal current in the

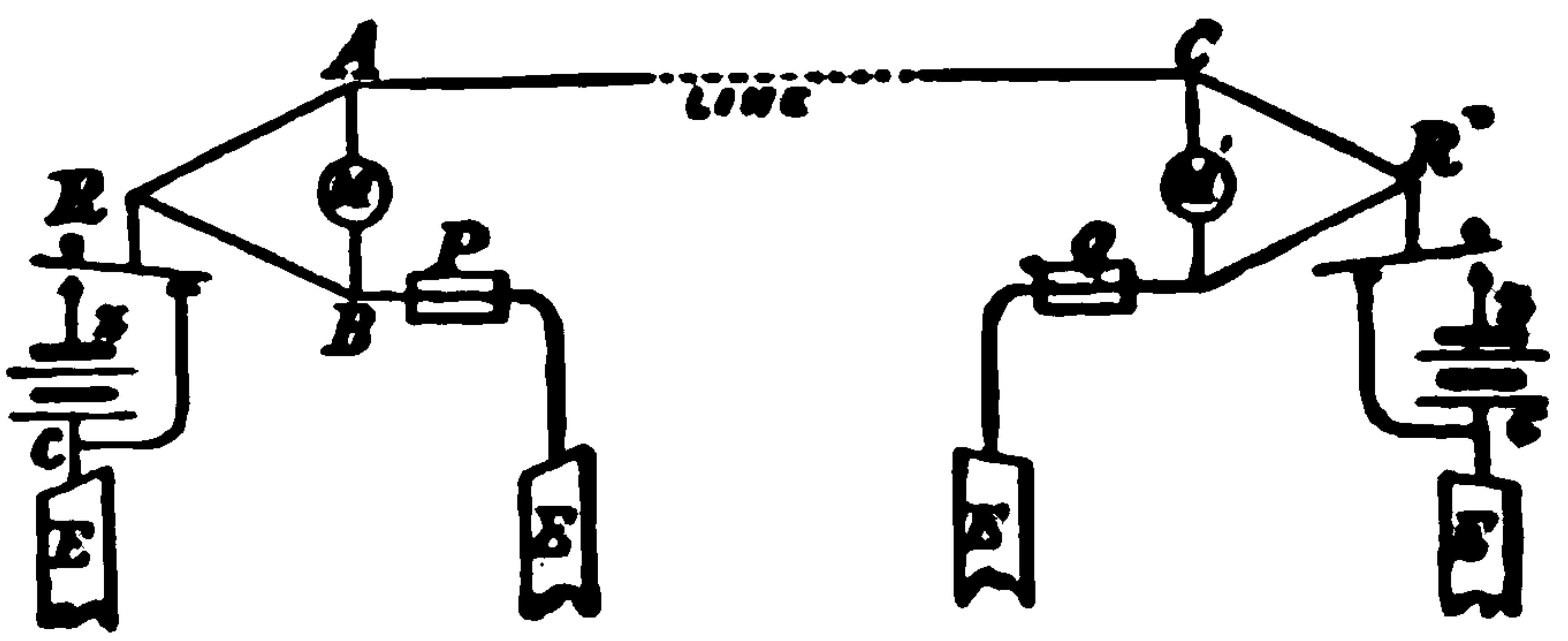


Fig. 281.

opposite direction, the flow through the line will cease; but M will now show a signal, because, although no current flows through the line, the current in the branch RA will now flow down through M, as if it had come from the distant R′, so, whether the operator at R be signalling or not, M will respond to signals sent from R′. In duplexing long lines and cables condensers are employed in the arms RA and RB of the bridge; and instead of a mere balancing resistance at P and Q there is used an "artificial cable," a combination of condensers and resistances to imitate the electrical properties of the actual line or cable between the stations.

The **Diplex** method of working consists in sending two messages at once through a wire in the same direction. To do this it is needful to employ one set of instruments which works only with currents in one given direction, and a second set which works only when the current, in either direction, exceeds a certain strength. The method involves the use of polarized relays, which, being themselves permanently magnetized, respond therefore only to currents in one direction, and of set-up non-polarized relays which will not respond to currents below a certain minimum. Two keys are used; one reversing the current and sending it in either positive or negative direction, the other sending current always in the same

direction, but sometimes weak, sometimes strong key controls the *direction*, the other the *strength* current.

The method used by Edison for transmitting is in Fig. 282. In the position shown the battery B terminals at N and current passing fr through K_2 to the sp and thence to P. H K′ is worked, the c flow into or out of th and, if a polarized r inserted at the dist ceiving station, it wi its sounder only for c in one direction, as s K′, no matter whethe currents are strong o As shown in the figu second battery B′, has more cells than B open circuit. If, ho

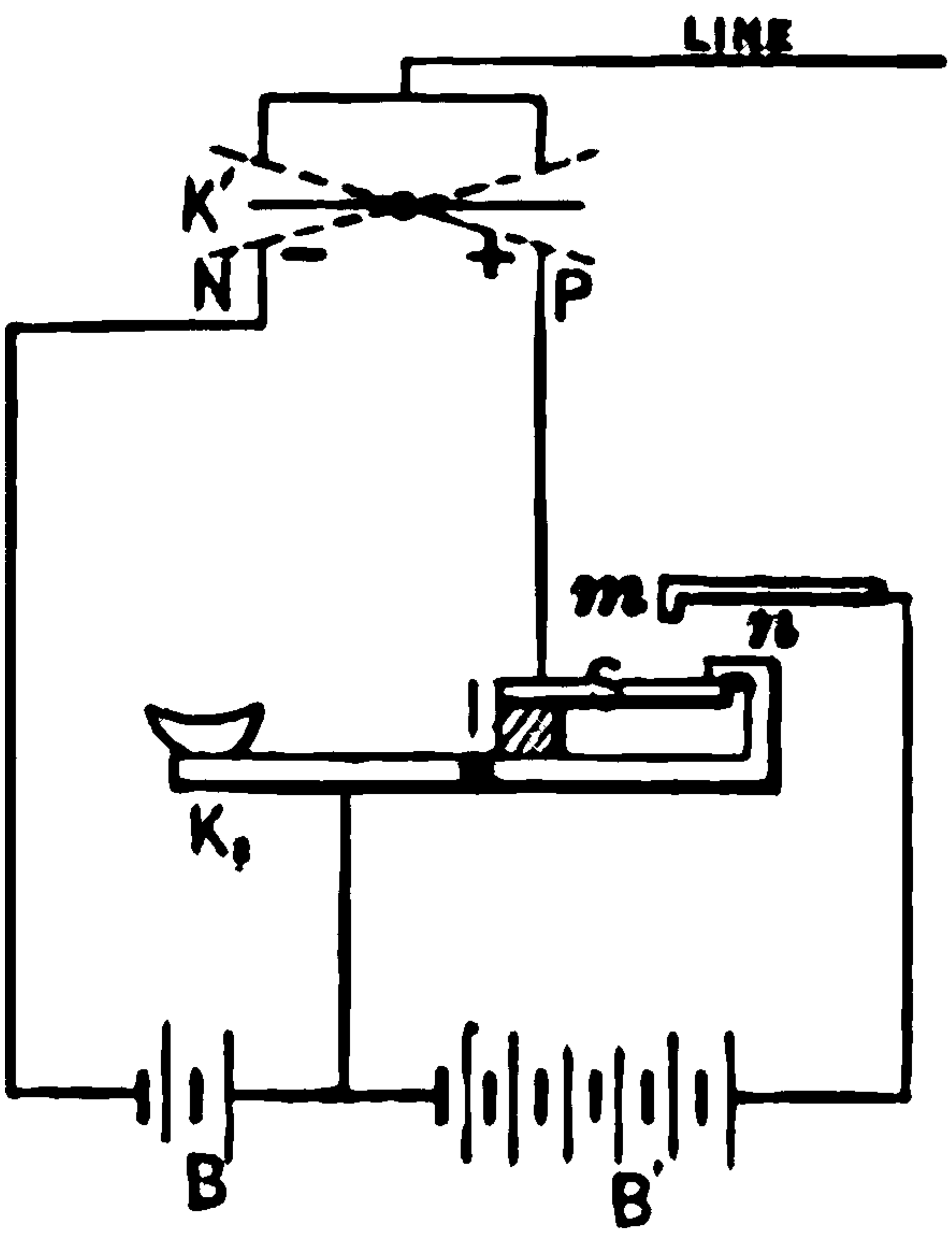


Fig. 282.

K_2 be depressed, the spring S comes into contact w point *m* and breaks contact with *n*, so that now the range of battery is thrown into operation. Wh K_2 is depressed, therefore, the points N and P retai polarity, but the current is of three or four tin original strength. All contacts are made by s properly adjusted so that K_2 never breaks the circ producing the change of strength of current. Th sage transmitted by K_2 is received on a non-po relay, the tongue of which is controlled by a spr adjusted that the weak currents of battery B wi cause the electromagnets to pull over the armatur when K_2 is worked, the current due to B + B′ easil the armature over.

The Quadruplex method of working combin

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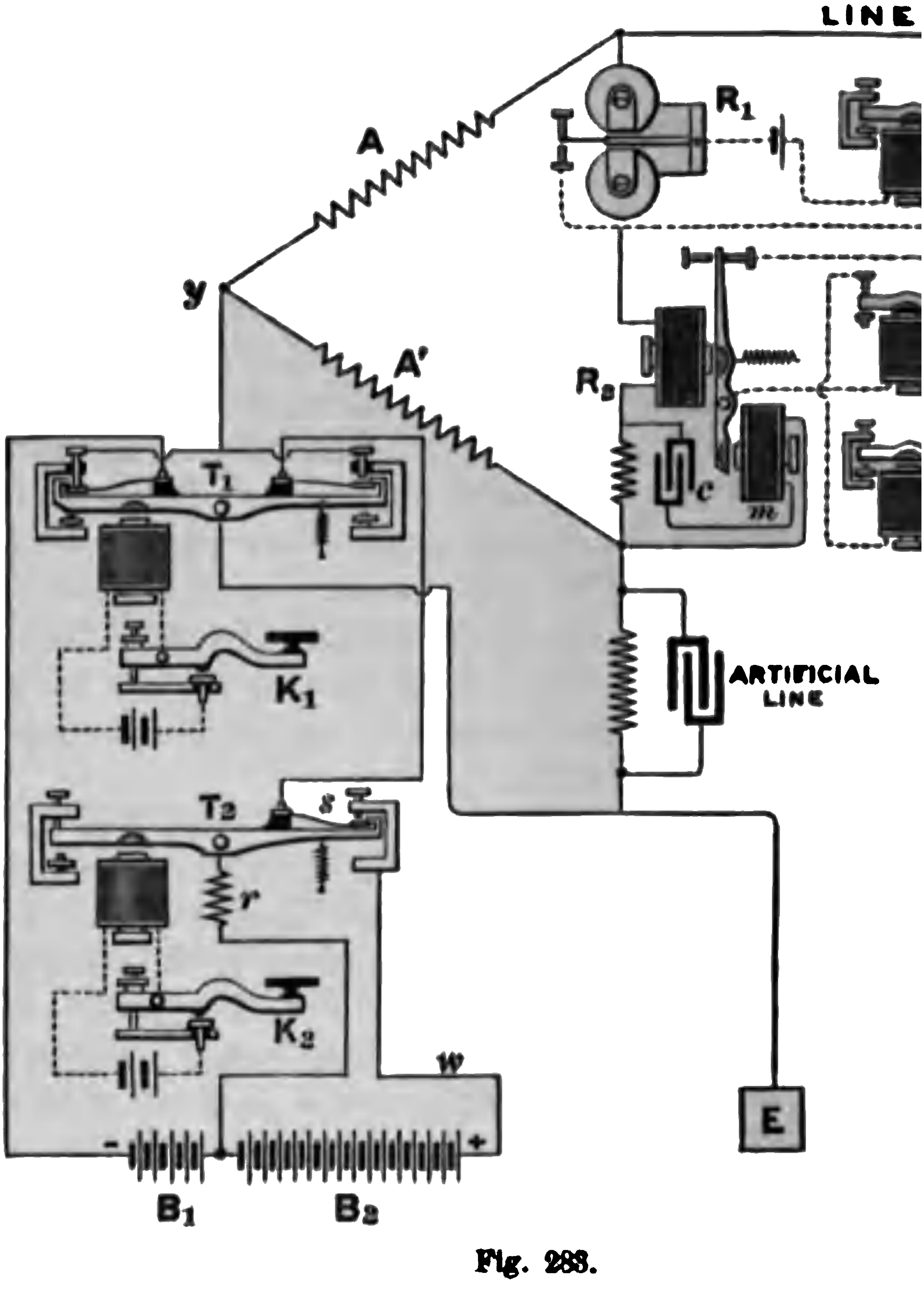


Fig. 283.

corresponds in its action to K_2 in Fig. 282, but instead of being worked by hand it is worked by an electromagnet in circuit with a small battery b_2 and operated by the key K_2. It is found that the electromagnet works the lever of T_2 with greater sharpness and precision than can be attained by hand with a key like K_2, and is not so fatiguing to the operator. So long as the lever of T_2 is in the position shown in the figure, the battery B_1 only is in circuit; but when the lever is depressed the small spring *s* connects wire *w* to the positive pole of the battery B_2, thereby causing a current of four-fold strength to flow to the line. The instrument T_1 is a *pole-changer* corresponding to K_1 in Fig. 282, and merely reverses the direction of the current in the line. The receiving instruments which are situated in the bridge are unaffected by the working of the transmitters K_1 and K_2 at the same end of the line, but respond to the signals sent from the distant station at the other end. The receiving instrument R_1 is a polarized relay which responds only to currents in the positive direction, whatever their strength; it therefore actuates the sounder S_1 only when the key K_1 of the distant station is depressed. The other receiving instrument R_2 is a non-polarized (or "neutral") relay, the lever of which is held back by an adjustable spring. It will respond to currents that flow in either the positive or the negative direction, but only when they are of the increased strength caused by depressing the key K_2 at the distant station. It may, however, happen that a reversal of the current by K_1 occurs in the middle of a signal with K_2; and this, if it occurred, would cause R_2 to let slip its armature for a fraction of a second, producing the effect of a double signal in the sounder S_2 if this were worked directly by R_2. To avoid this defect an intermediate relay (an up-righting sounder) S_3 is introduced in a local circuit of its own between R_2 and S_2. S_3 operates S_2 by contact with its back stop, so that a

momentary release of the lever of R_2 does not affect S_2 unless the interval of time is great enough for the lever of S_3 to reach its back stop. The additional magnet *m* in series with the condenser *c* is for the following purpose. While R_2 is reversing, the condenser discharges itself through *m* and thus holds the lever just at the dead point.

When the differential method is employed, the transmitting keys may be arranged as in Fig. 283, but (in

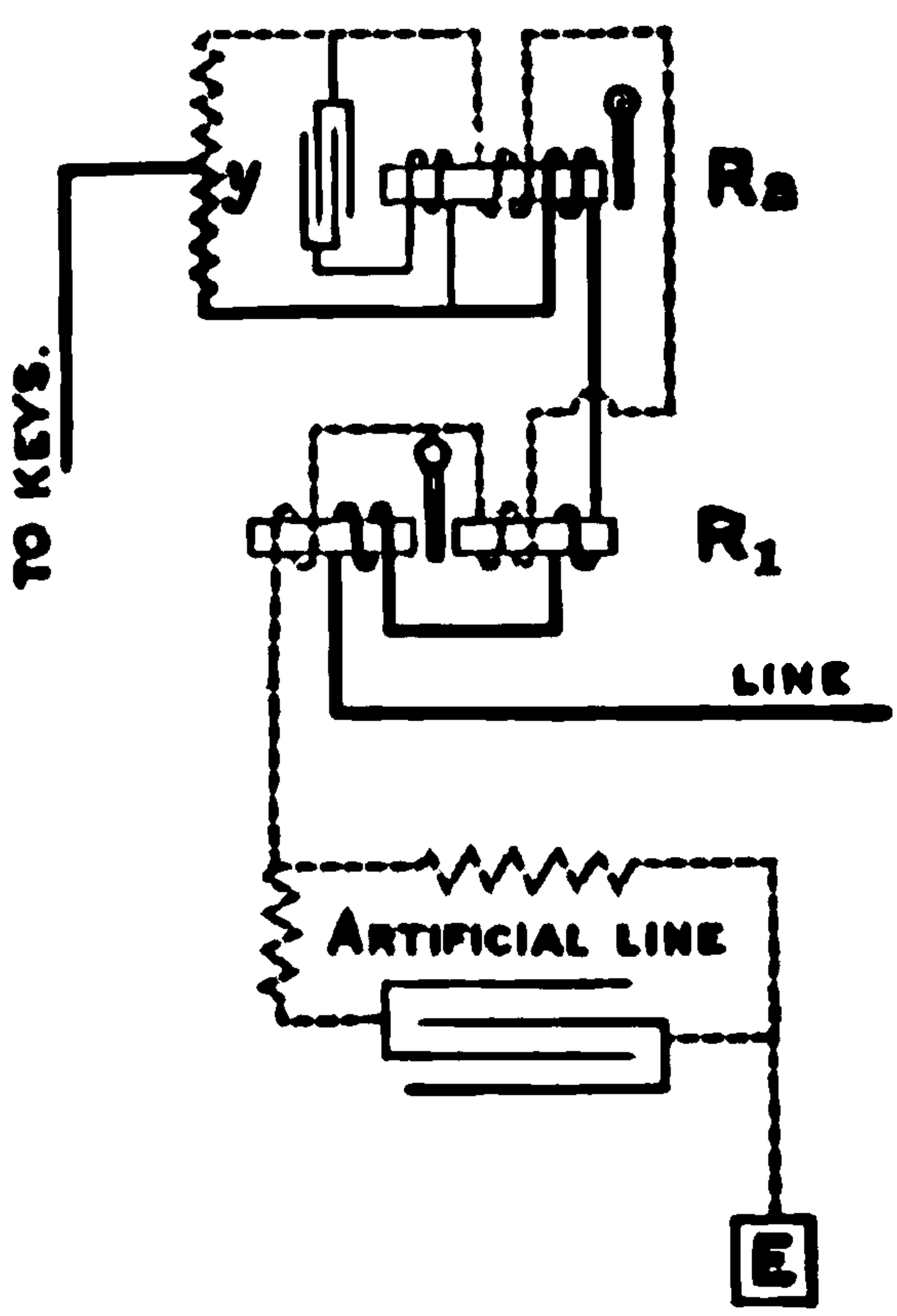


Fig. 283*a*.

lieu of the bridge arrangement) after the circuit divides into two at the point *y*, the two branches are wound differentially upon the two relays R_1 and R_2 as shown in Fig. 283*a*. One of these branches goes to the line, the other (shown dotted) goes to earth through resistances and condensers acting as an artificial line and constructed to balance the resistance and capacity of the actual line. Any current coming from the transmitters in the home station divides into two equal parts which circulate in

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cables laid in 1857 and 1866 respectively. In the latter cable, which is of the usual type of cable for long lines, the core is protected first by a stout layer of guttapercha, then by a woven coating of jute, and outside all an external sheath made of ten iron wires, each covered with hemp. The *shore ends* are even more strongly protected by external wires.

505. Speed of Signalling through Cables. — Signals transmitted through long cables are retarded, the retardation being due to two causes.

Firstly, The self-induction of the circuit prevents the current from rising at once to its height, the retardation being expressed by Helmholtz's equation (Art. 460).

Secondly, The cable in its insulating sheath, when immersed in water, acts laterally like a Leyden jar of enormous capacity (as explained in Art. 274), and the first portions of the current, instead of flowing through, remain in the cable as an electrostatic *charge* on the surface of the guttapercha. For every separate signal the cable must be at least partially charged and then discharged. Culley states that when a current is sent through an Atlantic cable from Ireland to Newfoundland no effect is produced on the most delicate instrument at the receiving end for two-tenths of a second, and that it requires three seconds for the current to gain its full strength, rising in an electric wave which travels forward through the cable. The strength of the current falls gradually also when the circuit is broken. The greater part of this retardation is due to electrostatic charge, not to electromagnetic self-induction. The time required to transmit a given number of signals varies in proportion both to K the capacity and R the resistance of the cable: it is therefore proportional to KR, and as each of these quantities is proportional to the length of the cable, it follows that the retardation is proportional to the *square of the length* of the cable. The various means adopted to get rid of this retardation are explained in Art. 323.

It is usual to insert in the circuit at each end of the cable a condenser of several microfarads, through which the signals pass. The tendency of the condenser to discharge helps to *curb* the signals and make each shorter and sharper. It is theoretically possible (compare Art. 438) to compensate capacity by self-induction; but as the capacity of a cable is lateral, not longitudinal, and distributed all along it, the self-induction coils to compensate the retardation would have to be applied as shunts at intervals. A cable with a self-inductive shunt or leak at a point near its middle transmits signals more rapidly than one not so compensated.

506. Receiving Instruments for Cables. — The *mirror-galvanometer* of Lord Kelvin (Art. 215) was devised for cable signalling, the movements of the spot of light sweeping over the scale to a short or a long distance sufficing to signal the dots and dashes of the Morse code. Lord Kelvin's *Siphon Recorder* is an instrument which writes the signals upon a strip of paper by the following ingenious means: — The cable communicates with a delicately-suspended coil of wire that hangs between the poles of a powerful magnet. To the suspended coil is attached a fine siphon of glass suspended by a silk fibre, one end of which dips into an ink vessel. The ink makes marks upon a strip of paper (moved by clockwork vertically past the siphon), friction being obviated by giving the siphon a continual minute vibration. The siphon record is a wavy line having short and long waves for dots and dashes.

Lesson LII. — *Miscellaneous Telegraphs*

507. Multiplex Telegraphs. — Varley proposed to send messages by transmitting electrically musical tones, interrupted to sound as dots and dashes. This necessitated the transmission of currents either rapidly alternat-

ing or rapidly intermittent. Gray, who constructed *harmonic telegraphs* on this plan, found it possible to transmit five or six messages simultaneously in one line.

By using at each end of a line two synchronously revolving distributing switches, it is possible to send several messages at once through a line; the distributors (invented by Delany) causing each transmitting instrument to be in circuit with its corresponding receiving instrument for a small fraction of a second at regular short intervals.

508. Electric Bells. — The common form of *Electric Trembling Bell* (invented 1850 by John Mirand) consists of an electromagnet, which moves a hammer backward and forward by alternately attracting and releasing it, so that it beats against a bell. The arrangements of the instrument are shown in Fig. 285, in which E is the electromagnet and H the hammer. A battery, consisting of one or two Leclanché cells placed at some convenient point of the circuit, provides a current when required. By touching the "push" P, the circuit is completed, and a current flows along the line and round the coils of the electromagnet, which forthwith attracts a small piece of soft iron attached to the lever, which terminates in the hammer H. The lever is itself included in the circuit, the current entering it above and quitting it at C by a contact-breaker, consisting of a spring tipped with platinum resting against the platinum tip of a screw, from which a return wire passes back to the zinc pole of the battery. As soon as the lever is attracted forward the circuit is broken at C by the spring moving away from contact with the screw; hence the current stops, and the electromagnet ceases to attract the armature, but the momentum of the hammer carries it forward. Immediately afterwards, however, the hammer falls back, again establishing contact at C, whereupon the armature is once more attracted forward, and so on. The impulses would not, however, maintain the motion if it were not for

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spring is abandoned, the clock being driven
dulum, the "bob" of which is an electrom
nately attracted from side to side. The
maintaining a perfectly constant battery
prevented such clocks from coming into us

Electrically controlled clocks, governed by
central clock, have proved a more fruitful inv
these the standard timekeeper is construct
complete a circuit periodically, once every mi
minute. The transmitted currents set in m
hands of a system of dials placed at distan
causing an electromagnet placed behind e
attract an armature, which, acting upon a r
by a pawl, causes it to move forward throug
at each specified interval, and so carries the h
at the same rate as those of the standard cloc

Electric *chronographs* are used for mea
small intervals of time. A stylus fixed to t
of an electromagnet traces a line upon a pie
fixed to a cylinder revolving by clockwork.
sent through the coils of the electromagne
armature and causes a lateral notch in the li
Two currents are marked by two notches; a
interval of *space* between the two notches the
time which elapsed between the two currents
culated to the ten-thousandth part of a se
speed of rotation is accurately known. The v
which a cannon ball moves along the bore of
can be measured thus.

CHAPTER XIII

TELEPHONY

Lesson LIII. — *Electric Telephones*

510. Early Telephones. — The first successful attempt to transmit sounds electrically was made in 1861 by Reis, who succeeded in conveying musical and other tones by an imperfect telephone. In this instrument the voice was caused to act upon a point of loose contact in an electric circuit, and by bringing those parts into greater or less intimacy of contact (Art. 400), thereby varied the resistance offered to the circuit. The transmitting part of Reis's telephone consisted of a battery and a contact-breaker, the latter being formed of a tympanum or diaphragm of stretched membrane, capable of taking up sonorous vibrations, and having attached to it a thin elastic strip of platinum, which, as it vibrated, beat to and fro against the tip of a platinum wire, so making and breaking contact wholly or partially at each vibration in exactly the same manner as is done with the carbon contacts in the modern transmitters of Blake, Berliner, etc. The receiving part of the instrument consisted of an iron wire fixed upon a sounding-board and surrounded by a coil of insulated wire forming part of the circuit. The rapid magnetization and demagnetization of such an iron core will produce audible sounds (Art. 124). If the current vary, the iron wire is partially magnetized or

demagnetized, giving rise to corresponding vibrations of varying amplitudes and forms; hence such a wire will serve perfectly as a receiver to reproduce speech if a good transmitter is used. Reis himself transmitted speech with his instrument, but only imperfectly, for all tones of speech cannot be transmitted by abrupt interruptions of the current, to which Reis's transmitter is prone when spoken into, owing to the extreme lightness of the contact: they require gentle undulations, sometimes simple, sometimes complex, according to the nature of the sound. The vowel sounds are produced by periodic and complex movements in the air; the consonants being for the most part non-periodic. Reis also devised a second receiver, in which an electromagnet attracted an elastically-supported armature of iron, which vibrated under the attraction of the more or less interrupted current.

In 1876 Elisha Gray devised a transmitter in which a variable water-resistance (made by a platinum wire dipping into water) was acted upon by the voice. He designed an electromagnetic receiver.

Telephone receivers were invented by Varley and Dolbear, in which the attraction between the oppositely-electrified armatures of a *condenser* is utilized in the production of sounds. Dolbear's receiver consists merely of two thin metal disks, separated by a very thin air-space. As the varying currents flow into and out of this condenser the two disks attract one another more or less strongly, and thereby vibrations are set up which correspond to the vibrations of the original sound.

In 1876 Graham Bell invented the magneto-telephone. In this instrument the speaker talks to an elastic plate of thin sheet iron, which vibrates and transmits its every movement electrically to a similar plate in a similar telephone at a distant station, causing it to vibrate in an identical manner, and thereby to emit identical sounds. The transmission of the vibrations depends upon the principles of magneto-electric induc-

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telephone, the disk of the distant receiving telephone is forced to repeat, and it therefore throws the air into similar vibrations, and so reproduces the sound. Bell's method of transmitting was soon abandoned (except for very short lines). In modern telephonic work Reis's plan of using a separate transmitter with a battery is universal, the Bell instrument being used as a receiver only and not as a transmitter.

511. **Edison's Transmitter.** — Edison constructed a transmitting instrument, in which the vibrations of the voice, actuating a diaphragm of mica, made it exert more or less compression on a button of prepared lamp-black placed in the circuit. The resistance of this is affected by pressure of contacts; hence the varying pressures due to the vibrations cause the button to offer a varying resistance to any current flowing (from a battery) in the circuit, and vary its strength accordingly. This varying current may be received as before in an electromagnetic receiver of the type described above, and there set up corresponding vibrations. This instrument also has been abandoned in favour of transmitters of the microphone type. Edison also invented a receiver of singular power, which depends upon a curious fact discovered by himself, namely, that if a platinum point presses against a rotating cylinder of moist chalk, the friction is reduced when a current passes between the two. And if the point be attached to an elastic disk, the latter is thrown into vibrations corresponding to the fluctuating currents coming from the speaker's transmitting instrument.

512. **Microphones.** — Hughes, in 1878, discovered that a *loose contact* between two conductors, forming part of a circuit in which a small battery and a receiving telephone are included, may serve to transmit sounds without the intervention of any specific tympanum or diaphragm like those of Reis and Edison, because the smallest vibrations will affect the resistance (Art. 400) at the point of loose contact. The **Microphone** (Fig. 288)

embodies this principle. In the form shown in the figure, a small thin pencil of carbon is supported loosely between two little blocks of the same substance fixed to a sounding-board of thin pine-wood, the blocks being connected with one or two small cells and a Bell receiver. The amplitude of the vibrations emitted by the receiver may be much greater than those of the original sounds,

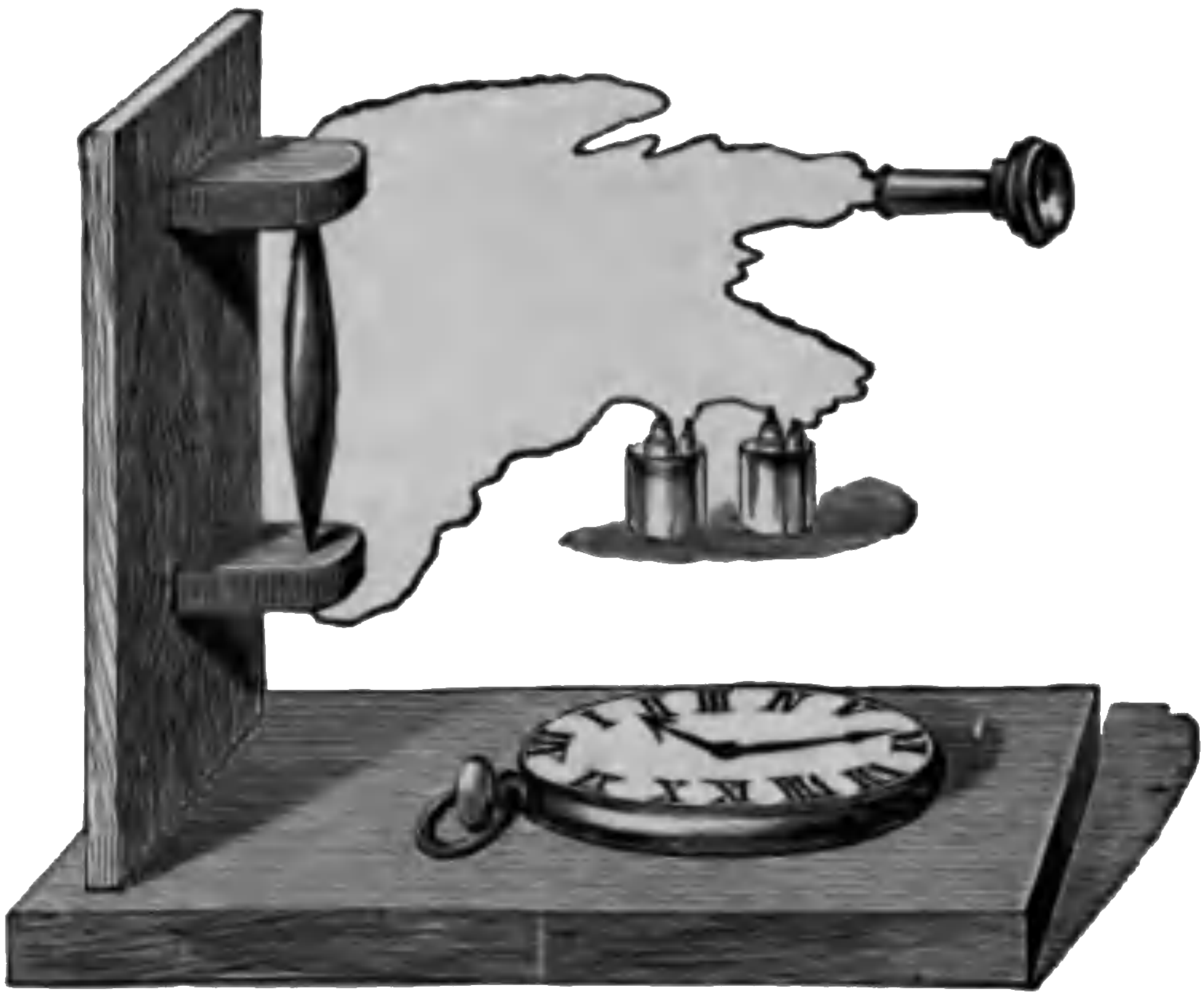


Fig. 288.

and therefore the microphone may serve, as its name indicates, to magnify minute sounds, such as the ticking of a watch or the footfalls of an insect, and render them audible. In modern telephony microphones under the name of *carbon transmitters* are in general use. Fig. 289*a* depicts the well-known Blake transmitter. The voice is directed through a shallow wooden mouth-piece M upon a diaphragm *d* of sheet iron held round its edge in a rubber packing. Behind it are the contact parts consisting of a pin of platinum mounted on a delicate spring *f* pressing delicately against a polished plug *k* of hard carbon mounted upon a stiffer spring *g*. The current

comes to the contact point by one spring and goes away by the other. A crooked back-lever *b* with an adjusting screw *j* serves to attain the proper initial pressure against the diaphragm. Another kind of transmitter, a modification of that of Hunnings' loud-speaking transmitter, is shown in Fig. 289*b*. The main feature of the Hunnings class of instruments is the use of granulated coke carbon placed loosely so that the voice can act upon its particles while the current finds its way through the mass. The voice thus acts on all the loose contacts at once, while the numerous paths for the current permit a larger current to be used than is possible with single contacts. In the form shown in the cut the granules are placed in a kind of box with a thin bottom of metal or carbon, on which the granules rest, and which is capable of vibrating with the voice. A piece of metal or carbon presses lightly on the granules from above, and serves as the other electrode. Much stronger currents can be used with such transmitters than with those having single contacts.

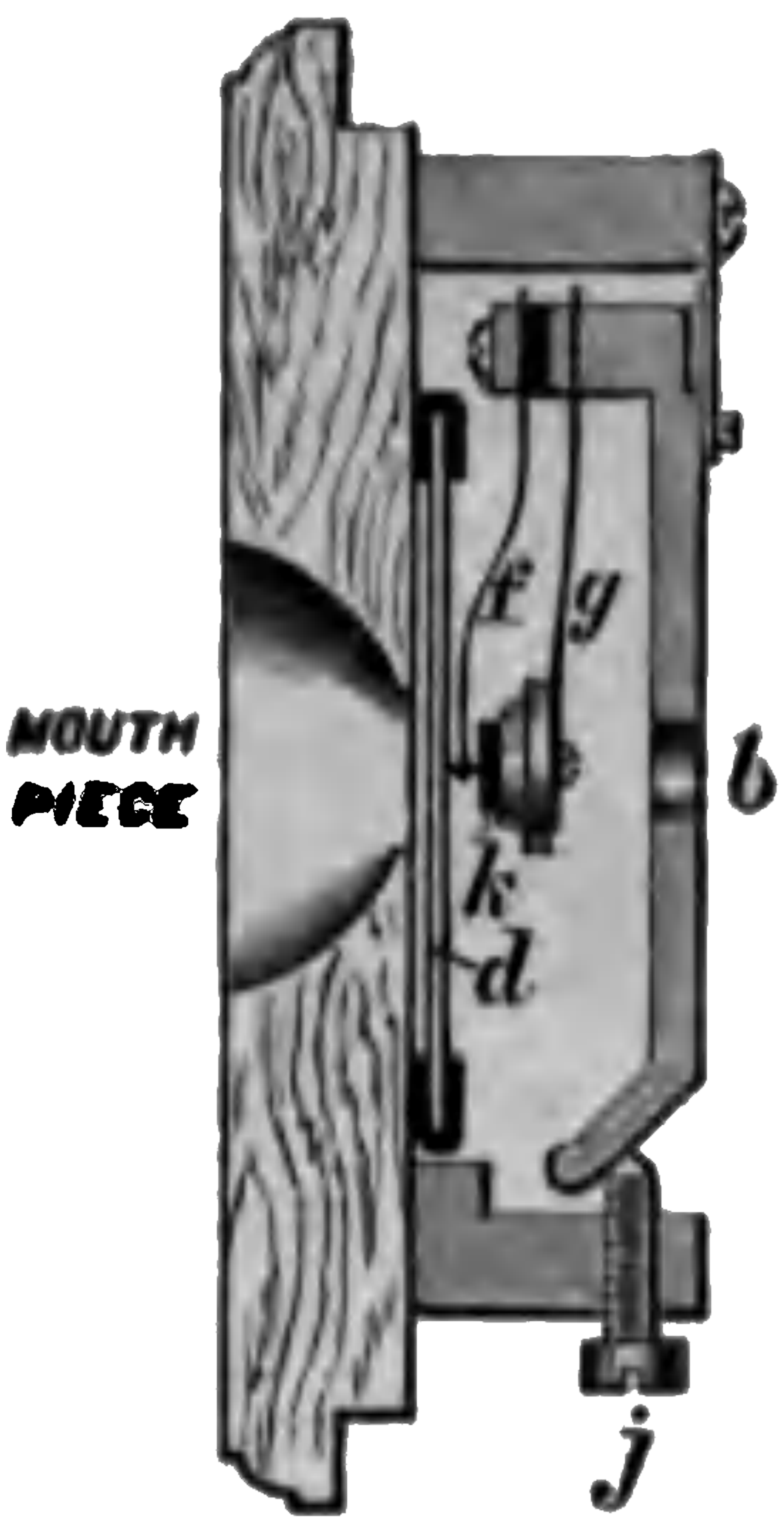


Fig. 289*a*.

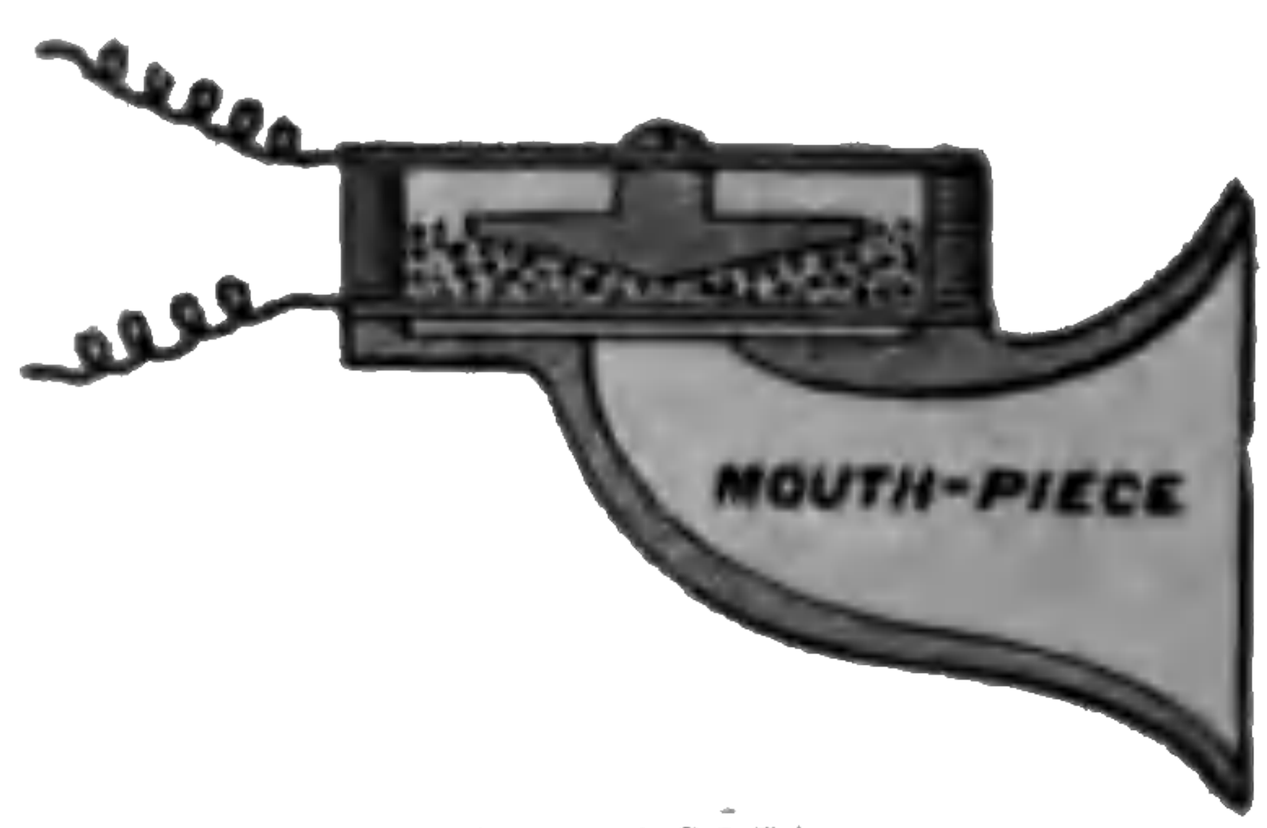


Fig. 289*b*.

513. Telephone Circuits. — The circuits required for using the transmitter and receiver, together with the call-bell and the automatic switch for throwing the battery out of circuit when not in use, are shown in diagram in Fig. 289*c*. The instruments here are a Blake's transmitter T and a Bell's receiver R. A single cell B_1 serves as battery for the transmitter, the additional battery B_2 being needed for ringing-up. [Frequently a small hand-

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municate by telephone with one another, the lines from each subscriber's instrument are brought to a central office known as a *telephone exchange.* Here each line terminates on a *switch-board* which is so arranged that the operator can in an instant make a connexion from the line of any one subscriber to that of any other, so that these two can talk together. But it is impossible in a few words to give a technical description of the complicated details of a telephone switch-board. In the best arranged telephone exchanges the earth is not used as a return conductor, twin wires going to each subscriber. Only by the use of such metallic circuits can interference from stray currents and cross talk be prevented.

514. Hughes's Induction Balance. — The extreme sensitiveness of Bell's receiver (Art. 510) to the feeblest currents has suggested its employment to detect currents

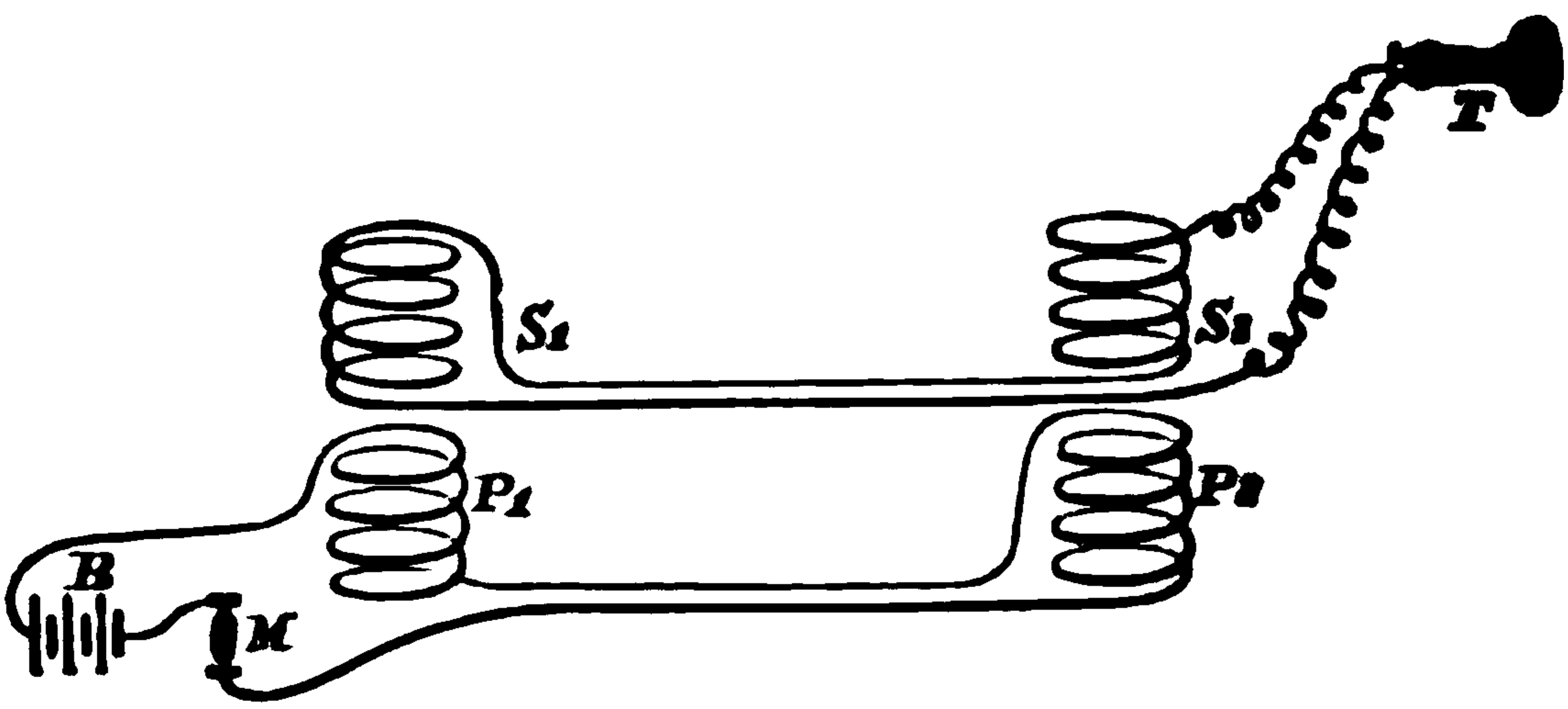


Fig. 289.

too weak to affect the most delicate galvanometer. The currents must, however, be intermittent, or they will not keep the disk of the telephone in vibration. Hughes applied this property of the telephone to an instrument named the Induction Balance (Fig. 289). A small battery B, connected with a microphone M, passes through two coils of wire P_1, P_2, wound on bobbins fixed on a suitable stand. Above each of these primary coils are

placed two secondary coils, S_1, S_2, of wire, of the same size, and of exactly equal numbers of turns of wire. The secondary coils are joined to a receiver T, and are wound in opposite directions. The result of this arrangement is that whenever a current either begins or stops flowing in the primary coils, P_1 induces a current in S_1, and P_2 in S_2. As S_1 and S_2 are wound in opposite ways, the two currents thus induced in the secondary wire neutralize one another, and, if they are of equal strength, balance one another so exactly that no sound is heard in the telephone. But a perfect balance cannot be obtained unless the resistances and the coefficients of mutual induction and of self-induction are alike. If a flat piece of silver or copper (such as a coin) be introduced between S_1 and P_1, there will be less induction in S_1 than in S_2, for part of the inductive action in P_1 is now spent on setting up currents in the mass of the metal (Art. 459), and a sound will again be heard in the telephone. But balance can be restored by moving S_2 farther away from P_2, until the induction in S_2 is reduced to equality with S_1, when the sounds in the telephone again cease. It is possible by this means to test the relative conductivity of different metals which are introduced into the coils. It is even possible to detect a counterfeit coin by the indication thus afforded of its conductivity. The induction balance has also been applied in surgery by Graham Bell to detect the presence of a bullet in a wound, for a lump of metal may disturb the induction when some inches distant from the coils.

CHAPTER XIV

ELECTRIC WAVES

Lesson LIV. — *Oscillations and Wav*

515. Electric Oscillations. — If a charged or Leyden jar is discharged slowly through a of high resistance, such as a nearly dry lin the charge simply dies away by a dischai increases in strength at first, and then grad away. If, however, the condenser is discharge a coil of wire of one or more turns (the spark b between polished knobs to prevent premature charges by winds or brushes) the effect is wholly for then the discharge consists of a number of e rapid oscillations or surgings. This is in cons the self-induction of the circuit, by reason of w 458) the current once set up tends to go on. rush more than e condenser, and cha opposite way; the reverse discharge, overdoes the disch charges the cond same way as at fi forth. Each succe

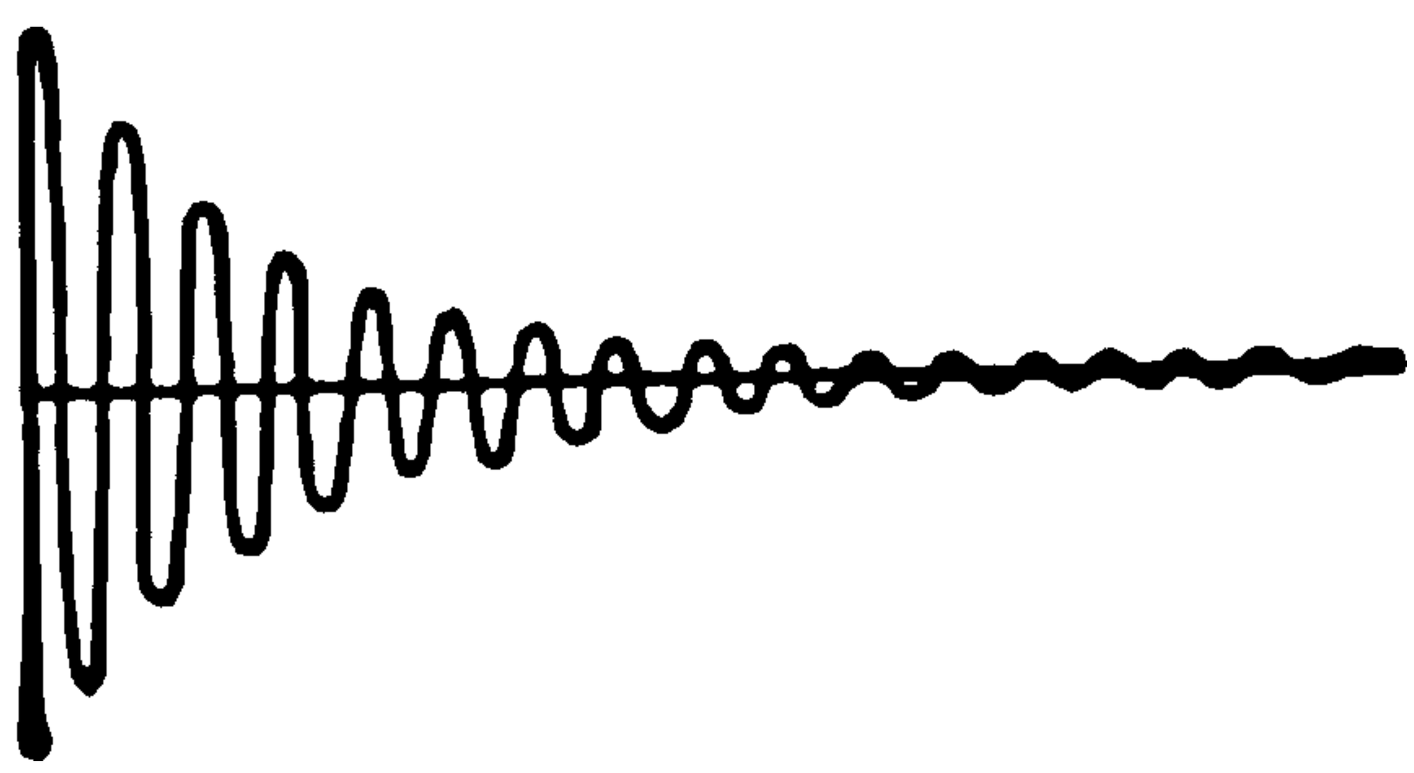


Fig. 290.

lation is feebler than the preceding, so that after of oscillations the discharge dies away as in Fig.

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instead of being a single instantaneous discharge, it exhibited definite fluctuations.* With very small resistances in the circuit, there was a true oscillation of the electricity backward and forward for a brief time. The period of the oscillations was found to be proportional to the square root of the capacity of the condenser. With a certain higher resistance the discharge became continuous but not instantaneous. With a still higher resistance the discharge consisted of a series of partial intermittent discharges, following one another in the same direction. Such sparks when viewed in the rotating mirror showed a series of separate images at nearly equal distances apart.

516. Electric Waves.—Though the increasing and dying away of currents, for example in cables, is sometimes loosely described as of "waves" of current, these phenomena are very different from those of true electric or electromagnetic *waves* propagated across space. In the case of true electric waves, portions of the energy of the current or discharge are thrown off from the conductor and do not return back to it, but go travelling on in space. If a current increases in strength the magnetic field around it also increases, the magnetic lines enlarging from the conductor outward, like the ripples on a pond. But as the current is decreased the magnetic lines all return back and close up upon the conductor; the energy of the magnetic field returns back into the system. But if for currents slowly waxing and waning we substitute electric oscillations of excessive rapidity, part of their energy radiates off into the surrounding medium as *electromagnetic waves*, and only part returns back. As will be presently set forth, these waves possess all the optical properties of light-waves, and can be reflected, refracted, polarized, etc.

It is a fundamental part of the modern views of electric action that while an electric displacement (Art. 57) is

* These electric oscillations were examined also by Schiller, Overbeck, Blaserna, and others, notably by Hertz; see Art. 520 below.

being produced in a dielectric, the effect in surrounding space is the same as if there had been a conductive instead of an inductive transfer of electricity. Maxwell gave the name of **displacement-current** to the rate of change of the displacement. Experiment proves that displacement-currents, while they last, set up magnetic fields around them; just as convexion-currents (Art. 397) and conduction-currents do.

517. Resonance. — The circumstance that when certain definite relations exist between the capacity and inductance of a circuit and the frequency of the periodic currents, the choking reactions of these properties neutralize one another, has been already alluded to in Art. 473. And we have seen (Art. 515) that a circuit with a certain self-induction, capacity, and resistance tends to oscillate electrically at a certain frequency. If it be placed in a medium through which electric waves of that frequency are passing in such a position that the electric and electromagnetic fields of the successive waves can induce currents in it, each wave will give a slight impulse to the readily-excited oscillations, which will grow in intensity, just as small impulses given to a pendulum at the right times will make it swing violently.

The following experiment of Oliver Lodge beautifully illustrates this phenomena of *resonance*, and at the same time the production of waves by an oscillatory discharge. Two Leyden jars, Fig. 291, are placed a little way apart from one another. One of them, charged from an influence machine not shown, is provided with a bent wire to serve as a discharging circuit, with a spark-gap S between the polished knobs at the top. The second jar is provided with a circuit of wire, the inductance of which

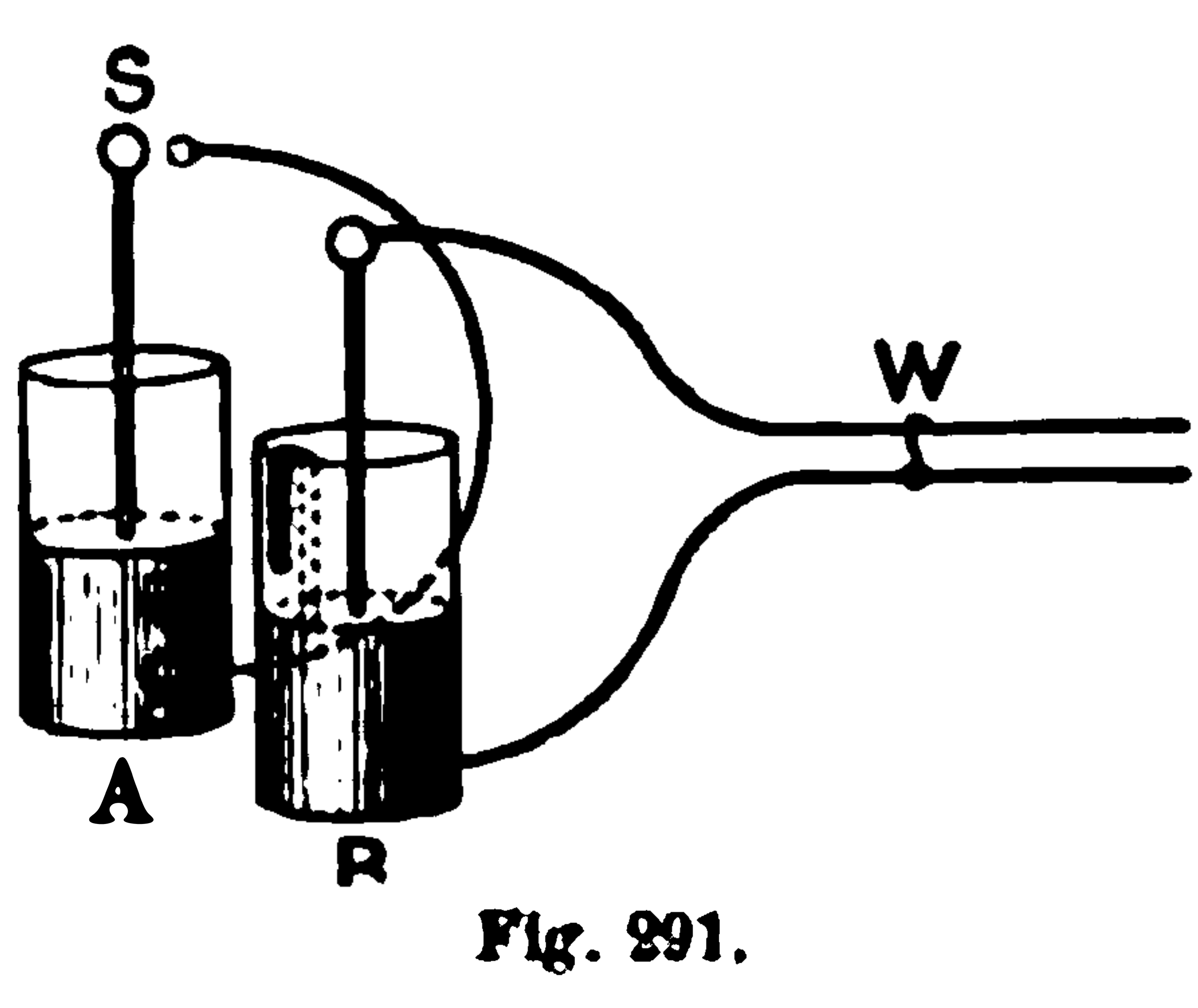


Fig. 291.

can be adjusted by sliding in or out a cross-piece W hooked upon the other portions. A strip of tinfoil is brought up from the inner coating over the lip of this jar, but does not quite touch the outer coating. If the two circuits are properly tuned together, whenever a spark passes in the gap at the top of A, surgings will be set up in the circuit of B which will cause the jar to overflow, producing a spark at the end of the strip.

Lesson LV.—*The Electromagnetic Theory of Light*

518. **Maxwell's Theory.**—In 1867 Clerk Maxwell put forward the theory that the waves of light are not mere mechanical motions of the ether, but that they are electrical undulations. These undulations are partly electrical and partly magnetic, oscillating electrical displacements being accompanied by oscillating magnetic fields at right angles to them, whilst the direction of propagation of the wave is at right angles to both. According to this theory the phenomena of electromagnetism and the phenomena of light are all due to certain modes of motion in the ether, electric currents and magnets being due to streams and whirls or other bodily movements in the substance of the ether, while light is due to vibrations to and fro in it.

An electric displacement in its growth or decay produces a magnetic force at right angles to itself; it also produces (by the peculiar action known as induction, an electric force which is propagated at right angles both to the electric displacement and to the magnetic force. Now it is known that in the propagation of light the actual displacements or vibrations which constitute the so-called ray of light are executed in directions at right angles to the direction of propagation. This analogy is an important point in the theory, and immediately suggests the question whether the respective rates

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Another consequence of the theory is that all conductors, since they dissipate the energy of the currents set up in them, ought to be *opaque* to light. Metallic conductors are, except when in very thin films. But electrolytic liquids are not opaque, the mechanism of their conduction being different (Art. 490). In some crystalline bodies which conduct electricity better in one direction than in another, the opacity to light differs correspondingly. Coloured crystals of *Tourmaline* conduct electricity better *across* the long axis of the crystal than *along* that axis. Such crystals are much more opaque to light passing *along* the axis than to light passing across it. And, in the case of rays traversing the crystal *across* the axis, the vibrations *across* the axis are more completely absorbed than those *parallel* to the axis: whence it follows that the transmitted light will be polarized.

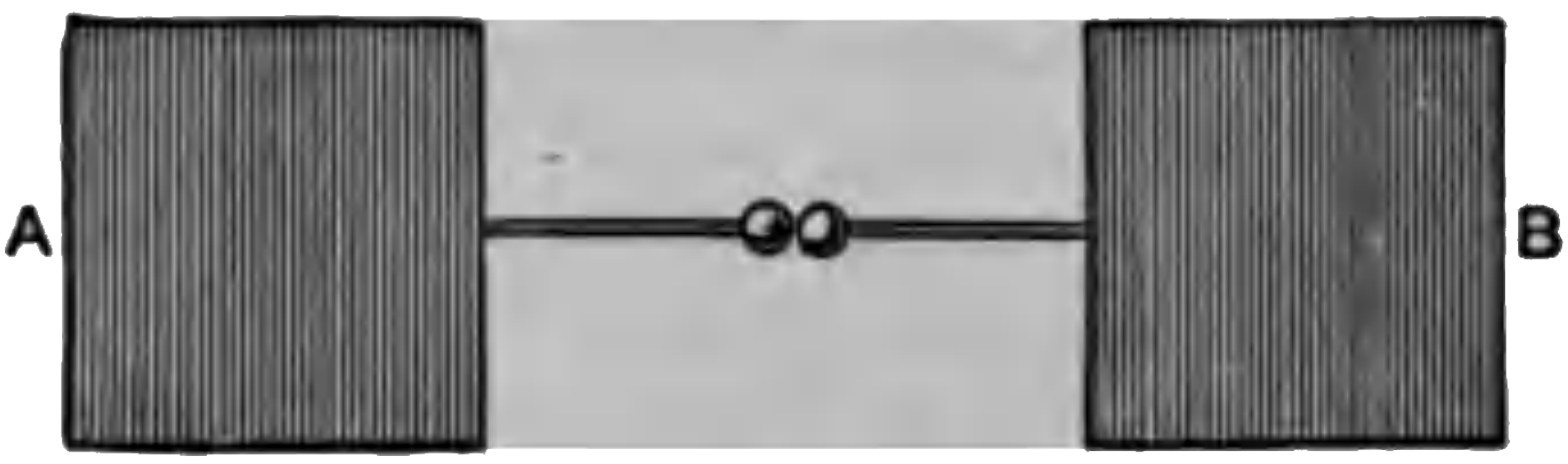
519. Energy Paths. — From Maxwell's equations Poynting in 1883 drew the conclusion that in all cases where energy is transferred in an electric system it flows parallel to the surfaces of both electric and magnetic equipotentials. What we call an electric current along a wire is rather a transfer of energy by an invisible mechanism in the medium outside the wire. Wherever in the wire there is resistance, wasting energy by degrading it into heat, at that point energy flows in *laterally* from the medium. According to this view, the service of the wire is merely to guide the energy flow going on outside it.* We know that when a current is started much energy is spent in building up around the conductor a magnetic field, the amount spent being $\frac{1}{2}LC^2$ (Art. 458). When the circuit is "broken" this energy flows on laterally into the wire, giving rise to the so-called extra-current sparks. According to Poynting's view, which has been independently elaborated by Heaviside, all the

* See particularly Oliver Lodge's *Modern Views of Electricity*.

energy flows in similarly. In the case of the transfer of energy in an alternate current transformer from the coils of the primary circuit to those of the secondary, it is pretty obvious that the flow of energy must take place *laterally* to the copper wires; and it also takes place laterally to the iron wires of the core, though this is not so obvious.

520. Researches of Hertz. — In 1888 Hertz found the most convincing experimental proofs of Maxwell's theory, and succeeded in producing electromagnetic waves in a way which permitted him to examine their propagation through space, and to show that, while they were much larger than ordinary waves of light, they possessed the same properties, travelled at the same speed, and were capable of being reflected, refracted, polarized, etc.

Of the power of oscillatory discharges to propagate disturbances in the surrounding space something was



OSCILLATOR.

Fig. 292.



RESONATOR.

Fig. 293.

already known. Henry had shown that they set up other sparks in distant conducting circuits. It had been discovered* that a spark-gap in the exciting circuit was necessary. Fitzgerald had definitely proposed to start waves by the oscillatory discharges of small condensers. But no one had systematically followed out the phenomena of propagation of the waves.

Hertz employed to start the waves an apparatus called an *oscillator* (Fig. 292), consisting of two metallic conductors (balls or plates) united by a metal rod, at the

* See paper by the author in the *Philosophical Magazine* (September, 1876).

middle of which was interposed a spark-gap between two well-polished knobs. And to detect the waves at a distance he employed a *resonator*, simply a circle or square of wire, having in it a spark-gap capable of minute adjustment. In one experiment the *oscillator* consisted of two zinc plates A and B (Fig. 292) with sides 40 cm. long mounted 60 cm. apart, and having stout copper wires leading to a spark-gap between very brightly polished brass balls. A dry wood stand was a sufficient insulator. The *resonator* to match was a circle 35 cm. in radius. To experiment with this apparatus the oscillator is joined to a small induction coil. When

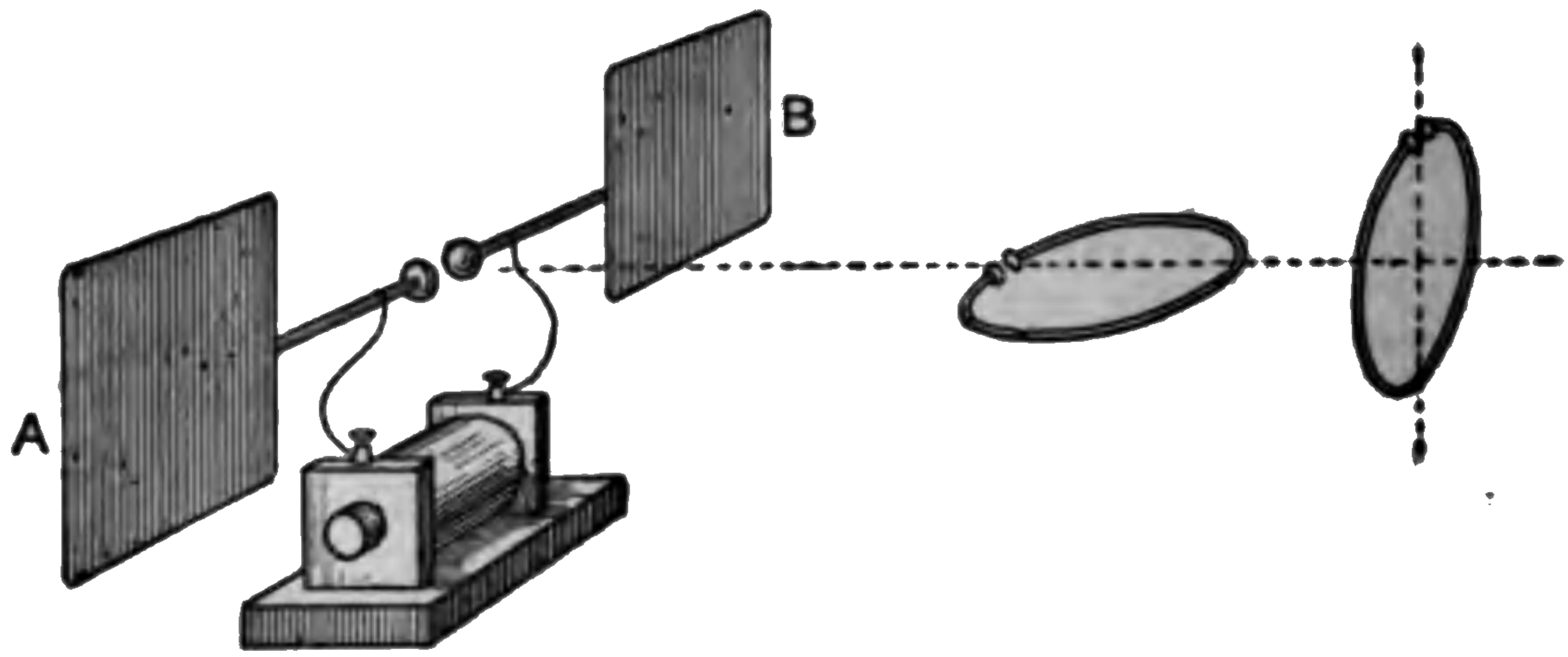


Fig. 294.

a spark snaps across the gap it sets up a temporary conducting path for the surgings that follow. For a rush of current from left to right overcharges the right-hand plate, and so there follows a rush back from right to left, and so on. Each spark sent by the coil across the gap consists of a dozen or so oscillations each lasting less than 1/100,000,000 of a second, the period being determined (Art. 515) by the capacity and inductance of the apparatus; the discharges surging backward and forward from A to B until they die out (Fig. 290). Let the line drawn horizontally in Fig. 294 be termed the *base line*, and let the line AB be termed the line of oscillation. Then if the resonator is placed with its centre on the base line at a few feet away from the oscillator and is turned into various positions,

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gap resonator is only one means of detecting electric waves. A prepared frog's leg (Art. 255) may be used instead of a spark-gap. A sensitive vacuum tube, especially if primed by application with a battery of some hundreds of small cells not quite able of themselves to start a spark, forms a good explorer. Electrometers; thin wires capable of expanding when heated by the induced currents; and galvanometers in circuit with the gap, are amongst the possible means. Best of all is Lodge's device of a tube partly filled with coarse iron filings, inserted in circuit with a galvanometer and a single cell. The resistance of the filings is very great, and little current flows, until an electric wave impinges upon the tube, when at once the filings conduct (compare Art. 400 on conductance of powders). On lightly tapping the tube the filings fall back into their former state. Using such a detector, and an oscillator consisting of a highly polished brass ball between two smaller balls, Lodge has shown how these electric waves can pass hundreds of feet through walls and floors of houses. Care must be taken to screen off with metallic screens the effects of stray sparks.

522. Properties of Electric Waves. — The universal equation connecting frequency n, wave-length λ, and velocity of propagation v is: $v = n\lambda$. Taking v (in air) as 3×10^{10} (cms. per sec.) as the velocity of light, and the measured length of the red waves (the longest visible) as 0·000076, it follows that the frequency of oscillation of these must be no less than 395×10^{12}. The waves artificially produced by electric oscillations are of much lower frequency than these, and their wave-length proportionally longer. Their wave-length depends on the size of the apparatus used as oscillator, just as the note emitted by an iron cylinder when struck on its end depends on the length of the cylinder. The wave-length of waves emitted from an oscillator consisting of a wire with a small capacity at each end is twice the length of the wire. That of waves emitted from

a sphere (Fig. 295) of diameter d is $2\pi d/\sqrt{3}$ or 3·6 d: but they die out after about 1 vibration. If a spark-gap is made between two knobs across the diameter of a hollow cylinder, the wave-length of the waves emitted from the end of the cylinder is about equal to its diameter, and the vibrations are numerous before all the energy has been radiated away. Using symmetrical pairs of condensers carefully adjusted Ebert has obtained oscillations that do not die out till after 20,000 periods.



Fig. 295.

The currents produced in wires by oscillations of such enormous frequency are only skin-currents (Art. 476), the inner part of the wire being idle. Hence for such currents the impeding resistance of a stout copper wire may be millions of ohms. One evidence of this is afforded by the tendency to *lateral discharge*. This is readily shown by connecting between the Leyden jars of an influence machine a loop of stout copper wire bent as in Fig. 296. When a discharge takes place between the knobs, there will be an oscillatory current set up between the outer coatings also; and this oscillatory current rather than flow along the metal loop will jump as a spark across the parts that lie nearest together. The tendency of lightning to produce lateral discharges is relied upon by Oliver Lodge in his contention as to the oscillatory character of the flash.

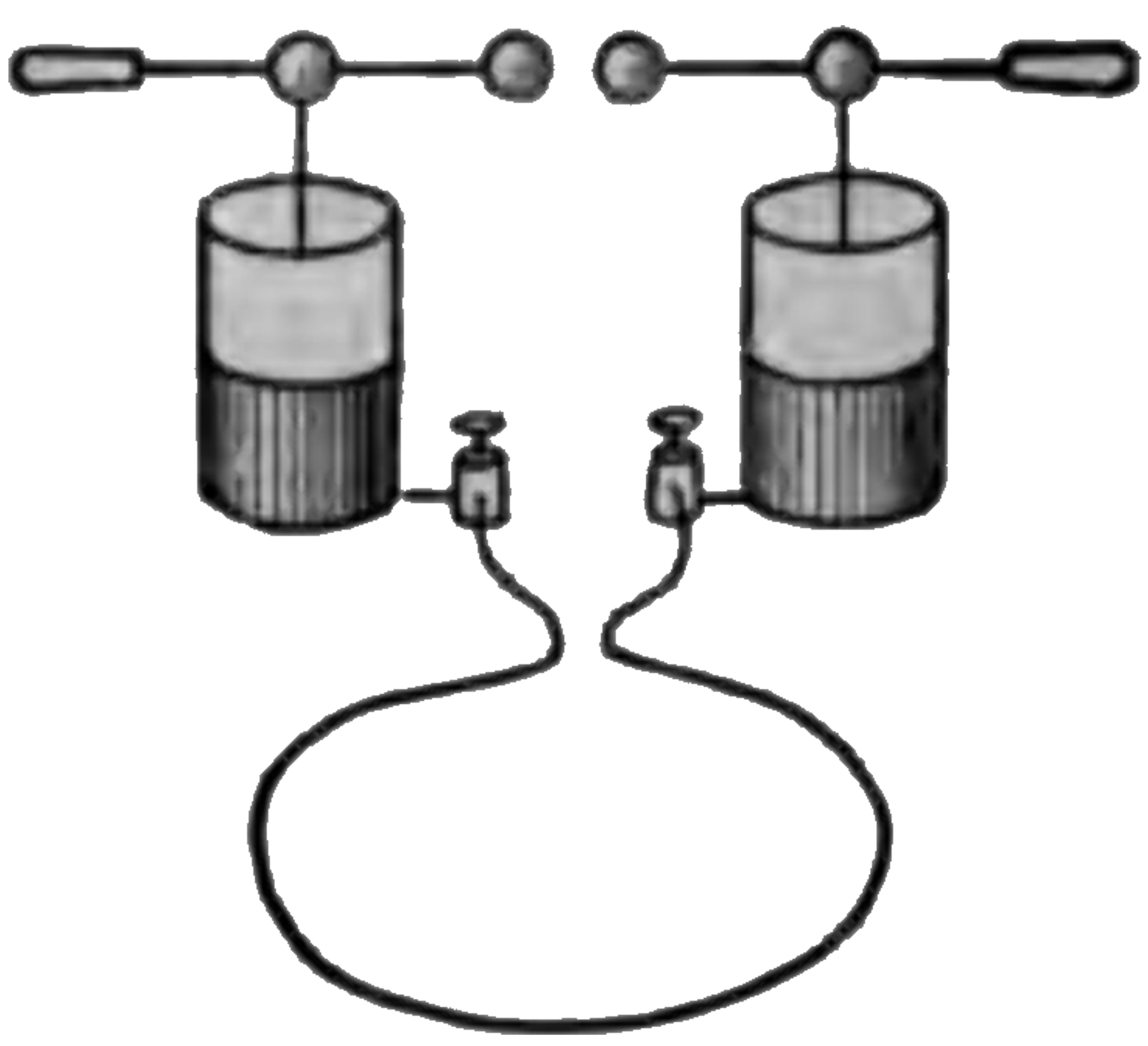


Fig. 296.

523. Travelling of Waves along Wires. — If an

oscillatory spark is sent into one end of a lon the time that the second pulsation reaches its the first will have travelled a certain distance v be called the wave-length of the disturbance. to Maxwell's theory the velocity of propagati equal to that of light, the energy really travellin the air, and settling down laterall wire. It appears from experimen velocity of a wave guided by the same as that of a wave tra free air. That the speed of tra independent of the thickness or m the wire was proved in 1870 by V using the device of Fig. 297. oscillatory discharge be sent by a into a rectangular circuit ABCD, spark-gap PQ midway between I It is evident that if G is midway

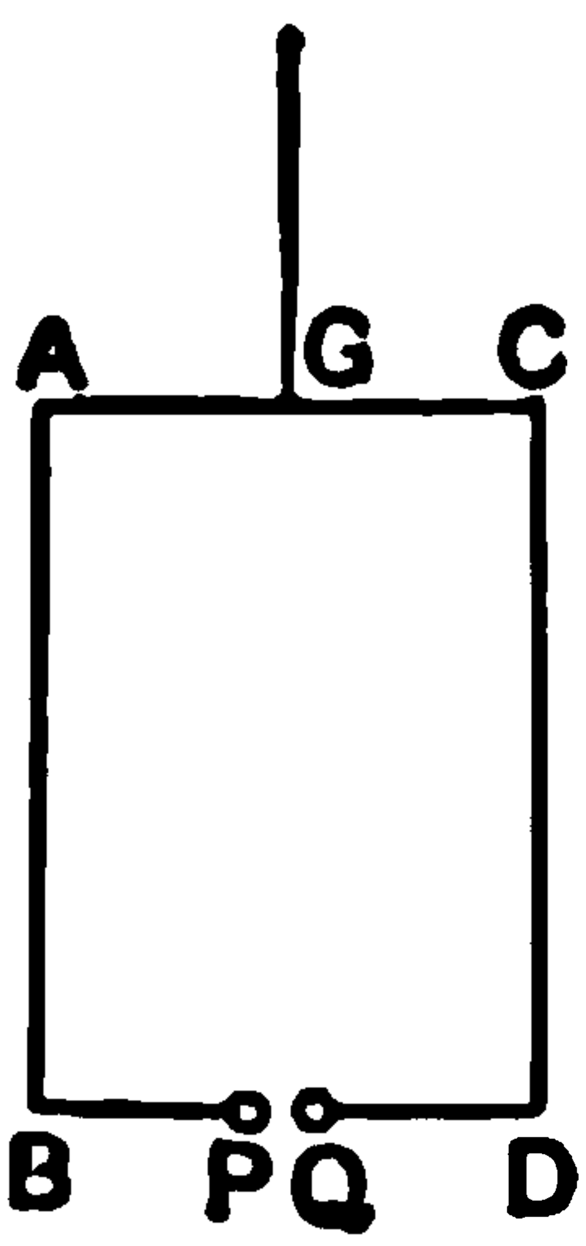


Fig. 297.

A and C the impulses will arrive simultaneo and Q if both sides of the system are alike; will be no spark. If now one side, say CD, be iron and the other, AB, of copper, it will be fo still the discharge must be led in at G, exactl if there is to be no spark.

Lesson LVI. — *Other Relations between Ligh Electricity*

524. Electro-optical Phenomena. — Of l several important relations have been observed electricity and light. These observations may fied under the following heads: —

(i.) Production of double refraction by stress.

(ii.) Rotation of plane of polarization of

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vegetable origin exhibit an action in the ne
tion, as if they had contracted along the e
It is found that the difference of retardat
the ordinary and extraordinary waves per u
of the dielectric *is proportional to the square*
ant electric force. The axis of double
along the line of the electric force. Quincke
out that these phenomena can be explained
ence of electrostatic expansions and contrac
in Art. 300.

526. Magneto-optic Rotation of the Pla zation of Light. — In 1845 Faraday discov wave of light polarized in a certain plane ca round by the action of a magnet, so that th are executed in a different plane. The plane beam is polarized can be detected by observin a second Nicol prism (or tourmaline), foi polarizer is opaque to waves polarized in a pl angles to that plane in which it would its light. Faraday caused a polarized beam to p a piece of a certain "heavy glass" (consisti borate of lead), lying in a powerful magne tween the poles of a large electromagnet, coils of which a current could be sent. In the emerging beam was placed as analyzer a s prism which had been turned round until a was extinguished. In this position its own pl metry was at right angles to the plane of pol the beam. On completing the circuit, light seen through the analyzing Nicol prism, provi waves had been twisted round into a new which the plane of polarization was no long angles to the plane of symmetry of the analy the analyzing Nicol prism was itself turned re position could be found (at right angles to th polarization of the waves) at which the ligh more extinguished. *The direction of the magne*

tion of the plane of polarization is the same (for *diamagnetic* media) *as that in which the current flows which produces the magnetism.* Verdet discovered the important law that, with a given material, *the amount of rotation is proportional to the strength of the magnetic force* H. In case the waves do not pass straight along the direction of the field, the amount of rotation is proportional *to the cosine of the angle* β *between the direction of the beam and the lines of force.* It is also proportional *to the length* l *of the material through which the waves pass.* These laws are combined in the equation for the rotation θ:

$$\theta = w \cdot \mathrm{H} \cdot \cos\beta \cdot l,$$

where w is a coefficient which represents the specific magnetic rotatory power of the given substance, and is known as *Verdet's constant.* Now, $\mathrm{H} \cdot \cos\beta \cdot l$ is the difference of magnetic potential between the point A where the wave enters and B where it leaves the medium. Hence

$$w = \frac{\theta}{\mathrm{V_B} - \mathrm{V_A}}.$$

The value of Verdet's constant for yellow sodium light, at 18° C., has been carefully determined. Its value (in radians per unit fall of magnetic potential) is, in bisulphide of carbon $1{\cdot}222 \times 10^{-5}$; in water $0{\cdot}375 \times 10^{-5}$; in heavy glass $2{\cdot}132 \times 10^{-5}$. For diamagnetic substances the coefficient is usually positive; but in the case of many magnetic substances, such as solutions of ferric chloride, has a negative value (*i.e.* in these substances the rotation is in the opposite direction to that in which the magnetizing current flows). The phenomenon discovered by Hall (Art. 397) appears to be intimately related to the phenomenon of magneto-optic rotation. For light of different colours the rotation is not equal, but varies very nearly inversely as the square of the wave-length.

Gases also rotate the plane of polarization of light in

a magnetic field with varying amounts; coal-gas and carbonic acid being more powerful than air or hydrogen; oxygen and ozone being negative. The rotation is in all cases very slight, and varies for any gas in proportion to the quantity of gas traversed. H. Becquerel has shown that the plane of the natural polarization of the sky does not coincide with the plane of the sun, but is rotated by the influence of the earth's magnetism through an angle which, however, only reached 59′ of arc at a maximum on the magnetic meridian.

We have seen (Arts. 126, 397, and 398) what evidence there is for thinking that magnetism is a phenomenon of rotation, there being a rotation of *something* around an axis lying in the direction of the magnetization. Such a theory would explain the rotation of the plane of polarization of a ray passing through a magnetic field. For a ray of plane-polarized light may be conceived of as consisting of a pair of (oppositely) circularly-polarized waves, in which the right-handed rotation in one ray is periodically counteracted by an equal left-handed rotation in the other ray; and if such a motion were imparted to a medium in which there were superposed a rotation (such as we conceive to take place in every magnetic field) about the same direction, one of these circularly-polarized rays would be accelerated and the other retarded, so that, when they were again compounded into a single plane-polarized ray, this plane would not coincide with the original plane of polarization, but would be apparently turned round through an angle proportional to the superposed rotation.

527. **Kerr's Effect.**—Dr. Kerr showed in 1877 that a ray of polarized light is also rotated when *reflected at the surface of a magnet* or electromagnet. When the light is reflected at a pole the plane of polarization is turned in a direction contrary to that in which the magnetizing current flows. If the light is reflected at a point on the side of the magnet it is found that when the plane of polarization is parallel to the plane of incidence the rotation is in the same direction as that of the magnetizing current; but that, when the plane of polarization is perpendicular to the plane of incidence, the rotation is in the same direction as that of the

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varying intensity upon a receiver of selenium connected in circuit with a small battery and a Bell telephone receiver (Art. 510) in which the sounds are reproduced by the variations of the current.

Similar properties are possessed, to a smaller degree, by *tellurium*. Carbon is also sensitive to light.

530. Photo-chemical Cells. — About the middle of the present century Becquerel showed that when two plates of silver, coated with freshly deposited chloride of silver, are placed in a cell with water and connected with a galvanometer, a current is observed to pass when light falls upon one of the two plates, the exposed plate acting as an anode; and Minchin has more recently shown the efficiency of other photo-chemical combinations. Some of these are very sensitive to electric waves of greater wave-length.

531. Photo-electric Loss of Charge. — In 1887 Hertz made the discovery that a spark starts more readily between the balls of a discharger when illuminated by light that is rich in violet and ultra-violet rays (magnesium light, arc light, or spark of induction coil) than when not so illuminated. The effect varies with different metals, with their cleanness, the nature of the surrounding gas, with the kind of charge, and with the polarization of the light. In ultra-violet light freshly polished zinc in air rapidly discharges a negative charge, but not a positive one. On the other hand the peroxides, in an atmosphere of hydrogen, when so illuminated readily discharge positive charges. The effect is stronger when the plane of the vibration of the incident waves is at right angles to the surface than when the polarization is in a parallel plane. The phenomenon appears to be due to the small light-waves stimulating chemical reactions which do not occur except (Art. 322) by a species of electric exchange. In a strong magnetic field no such discharges occur. Hallwachs charged clean zinc plates positively by exposure to ultra-violet light.

θ in Degrees.	θ in Radians.	Sine θ.	Tangent θ.	Solid Angle $2\pi(1-\cos\theta)$.	Complement of $\theta=\phi$.
0°	0	0	0	0	90°
1	·0175	·0175	·0175	·000957	89
2	·0349	·0349	·0349	·003837	88
3	·0524	·0523	·0524	·00861	87
4	·0698	·0698	·0699	·01532	86
5	·0873	·0872	·0875	·02391	85
6	·1047	·1045	·1051	·03441	84
7	·1222	·1219	·1228	·04683	83
8	·1396	·1392	·1405	·06115	82
9	·1571	·1564	·1584	·07735	81
10	·1745	·1737	·1763	·09545	80
11	·1920	·1908	·1944	·1154	79
12	·2094	·2079	·2126	·1373	78
13	·2269	·2250	·2309	·1610	77
14	·2444	·2419	·2493	·1866	76
15	·2618	·2588	·2680	·2140	75
16	·2793	·2756	·2868	·2434	74
17	·2967	·2924	·3057	·2745	73
18	·3142	·3090	·3249	·3075	72
19	·3316	·3256	·3443	·3423	71
20	·3491	·3420	·3640	·3789	70
21	·3665	·3584	·3839	·4173	69
22	·3840	·3746	·4040	·4575	68
23	·4014	·3907	·4245	·4994	67
24	·4189	·4067	·4452	·5431	66
25	·4363	·4226	·4663	·5886	65
26	·4538	·4384	·4877	·6358	64
27	·4712	·4540	·5095	·6848	63
28	·4887	·4695	·5317	·7354	62
29	·5062	·4848	·5543	·7877	61
30	·5236	·5000	·5774	·8417	60
31	·5411	·5150	·6009	·8974	59
32	·5585	·5299	·6249	·9507	58
33	·5760	·5446	·6494	1·0136	57
34	·5934	·5592	·6745	1·0741	56
35	·6109	·5736	·7002	1·1362	55
36	·6283	·5878	·7265	1·1999	54
37	·6458	·6018	·7536	1·2652	53
38	·6632	·6157	·7813	1·3319	52
39	·6807	·6293	·8098	1·4002	51
40	·6981	·6428	·8391	1·4700	50
41	·7156	·6561	·8693	1·5412	49
42	·7330	·6691	·9004	1·6138	48
43	·7505	·6820	·9325	1·6879	47
44	·7679	·6947	·9657	1·7634	46
45	·7854	·7071	1·0000	1·8402	45
		Cosine φ	Cotangent φ	$2\pi(1-\sin\phi)$	φ in Degrees

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APPENDIX B

[ABSTRACT OF BULLETIN OF U. S. COAST AND GEODETIC SURVEY, DATED DECEMBER 27, 1893]

UNITS OF ELECTRICAL MEASURE

During the past few years the advance of knowledge and experience among electricians was such as to indicate that the time was ripe for the general adoption of the principal units of electrical measure. An International Congress of Electricians was aranged for, to meet in Chicago, during the World's Columbian Exposition of 1893. In this Congress the business of defining and naming units of measure was left to what was known as the "Chamber of Delegates," a body composed of those only who had been officially commissioned by their respective governments to act as members of said Chamber. The United States, Great Britain, Germany, and France were each allowed five delegates in the Chamber. Other nations were represented by three, two, and in some cases one. The principal nations of the world were represented by their leading electricians, and the Chamber embraced many of the most distinguished living representatives of physical science.

The delegates representing the United States have reported to the Honorable the Secretary of State, under date of November 6, 1893, giving the names and definitions of the units of electrical measure as unanimously recommended by the Chamber in a resolution as follows:

"*Resolved*, That the several governments represented by the delegates of this International Congress of Electricians be, and they are hereby, recommended to formally adopt as legal units of electrical measure the following: As a unit of resistance, the *international ohm*, which is based upon the ohm equal to 10^9 units of resistance of the Centimetre-Gramme-Second system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14·4521 grammes in mass, of a constant cross-sectional area and of the length of 106·3 centimetres.

"As a unit of current, the *international ampere*, which is one-tenth of the unit of current of the C.G.S. system of electromagnetic units, and which is represented sufficiently well for practical use by the unvarying current which, when passed through a solution of nitrate of silver in water, and in accordance with accompanying specifications,* deposits silver at the rate of 0·001118 of a gramme per second.

"As a unit of electromotive-force, the *international volt*, which is the electromotive-force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of one international ampere, and which is represented sufficiently well for practical use by $\frac{1000}{1434}$ of the electromotive-force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of 15° C., and prepared in the manner described in the accompanying specification.†

"As a unit of quantity, the *international coulomb*, which is the quantity of electricity transferred by a current of one international ampere in one second.

"As a unit of capacity, the *international farad*, which is the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity.

"As a unit of work, the *joule*, which is equal to 10^7 units of work in the C.G.S. system, and which is represented sufficiently

* In the following specification, the term silver voltameter means the arrangement of apparatus by means of which an electric current is passed through a solution of nitrate of silver in water. The silver voltameter measures the total electrical quantity which has passed during the time of the experiment, and by noting this time, the time average of the current, or if the current has been kept constant, the current itself can be deduced.

In employing the silver voltameter to measure currents of about one ampere, the following arrangements should be adopted:

The kathode on which the silver is to be deposited should take the form of a platinum bowl, not less than 10 centimetres in diameter and from 4 to 5 centimetres in depth.

The anode should be a plate of pure silver some 30 square centimetres in area and 2 or 3 millimetres in thickness.

This is supported horizontally in the liquid near the top of the solution by a platinum wire passed through holes in the plate at opposite corners. To prevent the disintegrated silver which is formed on the anode from falling on to the kathode, the anode should be wrapped round with pure filter paper, secured at the back with sealing wax.

The liquid should consist of a neutral solution of pure silver nitrate, containing about 15 parts by weight of the nitrate to 85 parts of water.

The resistance of the voltameter changes somewhat as the current passes. To prevent these changes having too great an effect on the current, some resistance besides that of the voltameter should be inserted in the circuit. The total metallic resistance of the circuit should not be less than 10 ohms.

† A committee, consisting of Messrs. Helmholtz, Ayrton, and Carhart, was appointed to prepare specifications for the Clark's cell. Their report has not yet been received. [It is substantially identical with the specification given in Appendix C, following, which is that adopted by the British Board of Trade.]

well for practical use by the energy expended in one second by an international ampere in an international ohm.

"As a unit of power, the *watt*, which is equal to 10^7 units of power in the C.G.S. system, and which is represented sufficiently well for practical work done at the rate of one joule per second.

"As the unit of induction, the *henry*, which is the induction in a circuit when the electromotive-force induced in this circuit is one international volt, while the inducing current varies at the rate of one ampere per second."

To make the use of these units obligatory in all parts of the country will require an act of Congress, but in the absence of that, it is within the power of the Secretary of the Treasury to approve their adoption for use in all Departments of the Government. This, indeed, is precisely the course long ago followed in reference to the ordinary weights and measures of commerce and trade. Congress has never enacted a law fixing the value of their units, but the Secretary of the Treasury was authorized to establish and construct standards for use in the various Departments of the Government. Uniformity has followed on account of the universal adoption of these standards by the several States.

The Government is itself a large consumer of electricity and electrical machinery, and for its own protection it is important that units of measure be adopted. With the approval, therefore, of the Honorable the Secretary of the Treasury, the formal adoption by the Office of Standard Weights and Measures of the names and values of units of electrical measure as given above, the same being in accord with the recommendations of the International Congress of Electricians of 1893, is hereby announced.

T. C. MENDENHALL,
Superintendent U. S. Coast and Geodetic Survey, and of Standard Weights and Measures.

Approved:
J. G. CARLISLE,
Secretary of the Treasury.

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dissolved with the aid of gentle heat, but the temperature to which the solution is raised should not exceed 30° C. Mercurous sulphate treated as described in 3 should be added in the proportion of about 12 per cent by weight of the zinc sulphate crystals to neutralize any free zinc oxide remaining, and the solution filtered, while still warm, into a stock bottle. Crystals should form as it cools.

5. *The Mercurous Sulphate and Zinc Sulphate Paste.* — Mix the washed mercurous sulphate with the zinc sulphate solution, adding sufficient crystals of zinc sulphate from the stock bottle to ensure saturation, and a small quantity of pure mercury. Shake these up well together to form a paste of the consistence of cream. Heat the paste, but not above a temperature of 30° C. Keep the paste for an hour at this temperature, agitating it from time to time, then allow it to cool; continue to shake it occasionally while it is cooling. Crystals of zinc sulphate should then be distinctly visible, and should be distributed throughout the mass; if this is not the case add more crystals from the stock bottle, and repeat the whole process.

This method ensures the formation of a saturated solution of zinc and mercurous sulphates in water.

To set up the Cell

The cell may conveniently be set up in a small test tube of about 2 centimetres diameter, and 4 or 5 centimetres deep. Place the mercury in the bottom of this tube, filling it to a depth of say 0·5 centimetre. Cut a cork about 0·5 centimetre thick to fit the tube; at one side of the cork bore a hole through which the zinc rod can pass tightly; at the other side bore another hole for the glass tube which covers the platinum wire; at the edge of the cork cut a nick through which the air can pass when the cork is pushed into the tube. Wash the cork thoroughly with warm water, and leave it to soak in water for some hours before use. Pass the zinc rod about 1 centimetre through the cork.

Contact is made with the mercury by means of a platinum wire about No. 22 gauge. This is protected from contact with the other materials of the cell by being sealed into a glass tube. The ends of the wire project from the ends of the tube; one end forms the terminal, the other end and a portion of the glass tube dip into the mercury.

Clean the glass tube and platinum wire carefully, then heat the exposed end of the platinum red hot, and insert it in the mercury in the test tube, taking care that the whole of the exposed platinum is covered.

Shake up the paste and introduce it without contact with the upper part of the walls of the test tube, filling the tube above the mercury to a depth of rather more than 1 centimetre.

Then insert the cork and zinc rod, passing the glass tube through the hole prepared for it. Push the cork gently down until its lower surface is nearly in contact with the liquid. The air will thus be nearly all expelled, and the cell should be left in this condition for at least 24 hours before sealing, which should be done as follows:

Melt some marine glue until it is fluid enough to pour by its own weight, and pour it into the test tube above the cork, using sufficient to cover completely the zinc and soldering. The glass tube containing the platinum wire should project some way above the top of the marine glue.

The cell may be sealed in a more permanent manner by coating the marine glue, when it is set, with a solution of sodium silicate, and leaving it to harden.

The cell thus set up may be mounted in any desirable manner. It is convenient to arrange the mounting so that the cell may be immersed in a water bath up to the level of, say, the upper surface of the cork. Its temperature can then be determined more accurately than is possible when the cell is in air.

In using the cell sudden variations of temperature should as far as possible be avoided.

The form of the vessel containing the cell may be varied. In the H-form, the zinc is replaced by an amalgam of 10 parts by weight of zinc to 90 of mercury. The other materials should be prepared as already described. Contact is made with the amalgam in one leg of the cell, and with the mercury in the other, by means of platinum wires sealed through the glass.

PROBLEMS AND EXERCISES

QUESTIONS ON CHAPTER I

1. In what respects does an electrified body differ from a non-electrified body?

2. Name some of the different methods of producing electrification.

3. A body is charged so feebly that its electrification will not perceptibly move the leaves of a gold-leaf electroscope. Can you suggest any means of ascertaining whether the charge of the body is positive or negative?

4. How would you prove that the production of a positive charge is accompanied by the production of an *equal* negative charge?

5. Describe an experiment to prove that moistened thread conducts electricity better than dry thread.

6. Why do we regard the two electric charges produced simultaneously by rubbing two bodies together as being of opposite kinds?

7. Explain the action of the electrophorus. Can you suggest any means for accomplishing by a rotatory motion the operations of lifting up and down the cover of the instrument so as to obtain a continuous supply instead of an intermittent one?

8. Describe the state of the medium between two oppositely charged bodies, and state how you would determine the direction of the lines of force at any point.

9. Explain the Torsion Balance, and how it can be used to investigate the laws of the distribution of electricity.

10. Describe what takes place as an electrified conducting ball is made to approach a large conducting surface. Show by diagram the direction and relative number of the lines of force.

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25. Define electric density. A charge of 248 units of electricity was imparted to a sphere of 4 centimetres radius. What is the density of the charge? *Ans.* 1·23 (nearly).

QUESTIONS ON CHAPTER II

1. A dozen steel sewing-needles are hung in a bunch by threads through their eyes. How will they behave when hung over the pole of a strong magnet?

2. Explain the operation of an iron screen in protecting a galvanometer needle from magnets in its vicinity, and state why it is not perfectly effectual.

3. Of what material, and of what shape, would you make a magnet which is required to preserve its magnetism unaltered for a very long time? Describe the process of tempering.

4. What is meant by the resultant magnetic force at a point?

5. Six magnetized sewing-needles are thrust vertically through six little floats of cork, and are placed in a basin of water with their N-pointing poles upwards. How will they affect one another, and what will be the effect of holding over them the S-pointing pole of a magnet?

6. What distinction do you draw between magnets and magnetic matter?

7. On board an iron ship which is laying a submarine telegraph cable there is a galvanometer used for testing the continuity of the cable. It is necessary to screen the magnetized needle of the galvanometer from being affected by the magnetism of the ship. How can this be done?

8. How would you prove two magnets to be of equal strength?

9. The force which a magnet-pole exerts upon another magnet-pole decreases as you increase the distance between them. What is the exact law of the magnetic force, and how is it proved experimentally?

10. Describe the behaviour of Ewing's model of molecular magnetism in a magnetic field, and show how it corresponds with the behaviour of iron when magnetized. Divide the process of magnetizing into three successive stages.

11. What force does a magnet-pole, the strength of which is 9 units, exert upon a pole whose strength is 16 units placed 6 centimetres away? *Ans.* 4 *dynes*.

12. How would you place a long magnet so that one of its poles deflects a compass while the other does not affect it?

13. Distinguish between the "strength" of a magnet and its "magnetic moment."

14. Describe an instrument for comparing the relative values of magnetic forces. How would you use it to compare the magnetic moments of two magnets? If their distances from the magnetometer are respectively 20 centimetres and 30 centimetres, what is the ratio of their magnetic moments?
Ans. 8 : 27.

15. Two magnets have the same pole strength, but one is twice as long as the other. The shorter is placed 20 centimetres from a magnetometer (using the end-on method); state at what distance the other must be placed in order that there may be no deflexion. *Ans.* 25·2 centimetres.

16. A pole of strength 40 units acts with a force of 32 dynes upon another pole 5 centimetres away. What is the strength of that pole? *Ans.* 20 units.

17. It is desired to compare the magnetic force at a point 10 centimetres from the pole of a magnet with the magnetic force at 5 centimetres' distance. Describe four ways of doing this.

18. Explain the phenomenon of Consequent Poles.

19. In what direction do the lines of magnetic induction (or "lines of force") run in a plane in which there is a single magnetic pole? How would you arrange an experiment by which to test your answer?

20. What is a *Magnetic Shell?* What is the law of the potential due to a magnetic shell?

21. A steel bar magnet suspended horizontally, and set to oscillate at Bristol, made 110 complete oscillations in five minutes; the same needle when set oscillating horizontally at St. Helena executed 112 complete oscillations in four minutes. Compare the horizontal component of the force of the earth's magnetism at Bristol with that at St. Helena.
Ans. H at Bristol : H at St. Helena : : 484 : 784.

22. Supposing the dip at Bristol to be 70° and that at St. Helena to be 30°, calculate from the data of the preceding question the total force of the earth's magnetism at St. Helena, that at Bristol being taken as 0·48 unit. *Ans.* 0·307.

23. A small magnetic needle was placed magnetically north of the middle point of a strong bar-magnet which lay (magnetically) east and west. When the magnet was 3 feet away from the needle the deflexion of the latter was 2°: when moved up

to a distance of 2 feet the deflexion was 6° 30'; an foot apart the deflexion was 43°. Deduce the la *action* of one magnet on another.

24. Describe how the daily irregularities of th netism are registered at different stations for com

QUESTIONS ON CHAPTER III

1. Show that the total of the differences of pot tact in three simple voltaic cells joined in series as great as the difference of potential in one cell, being the same in each.

2. Classify the different methods of preventin in voltaic cells, and state the advantages and dis using a strong depolarizer, such as chromic acid.

3. On what does the internal resistance of a ba Is there any way of diminishing it?

4. A current of 10 amperes flows for half an total quantity of electricity that passes. Also d by which the quantity is measured. *Ans.* 18

5. State from what source the energy yieldec cell is derived.

6. How is local action in a voltaic cell minimiz

7. Twenty-four similar cells are grouped tog rows of six cells each; compare the electromo the resistance of the battery thus grouped, wit motive-force and the resistance of a single cell.

Ans. The E.M.F. of the battery is six time cell. The total internal resistance is (times that of one cell.

8. Describe a form of cell that could be used a of E.M.F. State the essential qualities of such a

9. A piece of silk-covered copper wire is coil equator of a model terrestrial globe. Apply Am determine in which direction a current must be the coil in order that the model globe may represe tion of the earth magnetically.

Ans. The current must flow across the Africa to America, and across the America toward India; or, in other wo always from east toward west.

10. A current of ·24 amperes flows through a c seventy-two turns, the (average) diameter of the centimetres. What is the strength of the magnet the current produces at the centre of the coil?

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21. A plate of zinc and a plate of copper are united by copper wires to the two screws of a g They were then dipped side by side into a gla dilute sulphuric acid. The galvanometer needle a a deflexion of 28°, but five minutes later the (fallen to 11°. How do you account for this falling

22. Classify liquids according to their power (electricity. In which class would melted pewter c

23. Name the substances produced at the anode respectively during the electrolysis of the followin — *Water*, *dilute sulphuric acid*, *sulphate of copp* in water), *hydrochloric acid* (strong), *iodide of po* solved in water), *chloride of tin* (fused).

24. A current is sent through three electroly first containing acidulated water, the second sulph the third contains a solution of silver in cyanide (How much copper will have been deposited in th while 2·268 grammes of silver have been deposited cell? And what *volume* of mixed gases will have l at the same time in the first cell?

Ans. ·6656 grammes of copper and 351·4 metres of mixed gases.

25. A current passes by platinum electrodes t cells, the first containing a solution of blue vitrio phate), the second containing a solution of green vi sulphate), the third containing a solution of fe State the amounts of the different substances evo electrode by the passage of 1000 coulombs of ele

Ans. First Cell, { Anode ·0829 gramme of oxyg
Kathode ·3281 gramme of co

Second Cell, { Anode ·0829 gramme of oxyg
Kathode ·2902 gramme of iro

Third Cell, { Anode ·3673 gramme of chlo
Kathode ·1935 gramme of iro

26. The ends of a coil of fine insulated wire a with the terminals of a galvanometer. A steel b pushed *slowly* into the hollow of the coil and the suddenly. What actions will be observed on the galvanometer?

27. Round the outside of a deep cylindrical ja two separate pieces of fine silk-covered wire, each many turns. The ends of one coil are fastened those of the other to a sensitive galvanometer. W bar is poked into the jar a momentary current is ol galvanometer coils, and when it is drawn out ano tary current, but in an opposite direction, is observ these observations.

28. A casement window has an iron frame. The aspect is north, the hinges being on the east side. What happens in the frame when the window is opened?

29. Explain the construction of the induction coil. What are the particular uses of the condenser, the automatic break, and the iron wire core?

30. It is desired to measure the strength of the field between the poles of an electromagnet which is excited by a current from a constant source. How could you apply Faraday's discovery of induction-currents to this purpose?

31. A small battery was joined in circuit with a coil of fine wire and a galvanometer, in which the current was found to produce a steady but small deflexion. An unmagnetized iron bar was now plunged into the hollow of the coil and then withdrawn. The galvanometer needle was observed to recede momentarily from its first position, then to return and to swing beyond it with a wider arc than before, and finally to settle down to its original deflexion. Explain these actions, and state what was the source of the energy that moved the needle.

32. A tangent galvanometer, whose "constant" in absolute units was 0·08 was joined in circuit with a battery and an electrolytic cell containing a solution of silver. The current was kept on for one hour; the deflexion observed at the beginning was 36°, but it fell steadily during the hour to 34°. Supposing the horizontal component of the earth's magnetic force to be ·23, calculate the amount of silver deposited in the cell during the hour, the absolute electro-chemical equivalent of silver being 0·01134. *Ans.* 0·526 *gramme.*

33. A piece of zinc, at the lower end of which a piece of copper wire is fixed, is suspended in a glass jar containing a solution of acetate of lead. After a few hours a deposit of lead in a curious tree-like form ("Arbor Saturni") grows downwards from the copper wire. Explain this.

34. Explain the conditions under which electricity excites muscular contraction. How can the converse phenomenon of currents of electricity produced by muscular contraction be shown?

35. A certain piece of apparatus has two terminals on each side. To these a pair of wires, A and B, are attached at one side, and another pair at C and D. Examination with a voltmeter shows that the potential of A is higher than that of B, and that of C higher than that of D. Yet examination with an ampere-meter shows that a current is flowing from B to A through the apparatus, and another current from C to D through the other part of the apparatus. By which circuit is the energy coming in, and by which is it going out?

36. Show that if N magnetic lines are withdrawn from a circuit of resistance R, the quantity of electricity thereby transferred around the circuit (*i.e.* the time integral of the induced current) will be $Q = N/R$. (See Art. 225.)

37. The strength of the field between the poles of a large electromagnet was determined by the following means:—A small circular coil, consisting of 40 turns of fine insulated wire, mounted on a handle, was connected to the terminals of a long-coil galvanometer having a heavy needle. On inverting this coil suddenly, at a place where the total intensity of the earth's magnetic force was ·48 unit, a deflexion of 6° was shown as the first swing of the galvanometer needle. The sensitiveness of the galvanometer was then reduced to $\frac{1}{10}$ by means of a shunt. The little coil was introduced between the poles of the electromagnet and suddenly inverted, when the first swing of the galvanometer needle reached 40°. What was the strength of the field between the poles? *Ans.* 315·7 units.

QUESTIONS ON CHAPTER IV

1. Define the *unit* of electricity as derived in absolute terms from the fundamental units of *length*, *mass*, and *time*.

2. At what distance must a small sphere charged with 28 units of electricity be placed from a second sphere charged with 56 units in order to repel the latter with a force of 32 dynes? *Ans.* 7 *centimetres.*

3. Suppose the distance from the earth to the moon to be (in round numbers) 383×10^8 centimetres; and that the radius of the earth is 66×10^7 centimetres, and that of the moon 15×10^7 centimetres; and that both moon and earth are charged until the surface density on each of them is of the average value of 10 units per square centimetre. Calculate the electrostatic repulsion between the moon and the earth.

4. A small sphere is electrified with 24 units of + electricity. Calculate the *force* with which it repels a unit of + electricity at distances of 1, 2, 3, 4, 5, 6, 8, and 10 centimetres respectively. Then plot out the "*curve of force*" to scale; measuring the respective distances along a line from left to right as so many centimetres from a fixed point as origin; then setting out as vertical ordinates the amounts you have calculated for the corresponding forces; lastly, connecting by a curved line the system of points thus found.

5. Define electrostatic (or electric) "*potential*"; and calculate (by the rule given in *italics* in Art. 263) the potential at a point A, which is at one corner of a square of 8 centimetres' side, when at the other three corners B, C, D, taken in order, charges of + 16, + 34, and + 24 units are respectively placed. *Ans.* 8 (very nearly).

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that at the surface of B being +3. They are placed 2 centimetres apart. Find the force with which a + unit of electricity is urged from A towards B. Find also the work done by a + unit of electricity in passing from A to B.

Ans. Electric force from A towards B = 18·85 *dynes*; work done by unit in passing from A to B = 37·5 *ergs*.

18. What is meant by the *dimensions* of a physical quantity? Deduce from the Law of Inverse Squares the dimensions of electricity; and show by this means that electricity is not a quantity of the same physical dimensions as either *matter*, *energy*, or *force*.

19. Explain the construction and principles of action of the quadrant electrometer. How could this instrument be made self-recording?

20. Describe the construction of an electrostatic voltmeter, and state some of the advantages that this instrument possesses.

21. One of the two coatings of a condenser is put to earth, to the other coating a charge of 5400 units is imparted. It is found that the difference of potential thereby produced between the coatings is 15 (electrostatic) units. What was the capacity of the condenser? *Ans.* 360.

22. What is the meaning of *specific, inductive, capacity*? Why does hot glass *appear* to have a higher specific inductive capacity than cold glass?

23. Describe a method of mapping out the lines of force in an electrostatic field.

24. Two condensers of capacity 4 and 6 respectively are placed in parallel; and in series with them is placed another condenser having a capacity of 5 microfarads. Find the capacity of the whole combination. *Ans.* 3·$\dot{3}$.

25. Compare the phenomenon of the residual charge in a Leyden jar with the phenomenon of polarization in an electrolytic cell.

26. A condenser was made of two flat square metal plates, the side of each of them being 35 centimetres. A sheet of indiarubber ·4 centim. thick was placed between them as a dielectric. The specific inductive capacity of indiarubber being taken as 2·25, calculate the capacity of the condenser.

Ans. 548·8 *electrostatic units*.

27. Calculate (in electrostatic units) the capacity of a mile of telegraph cable, the core being a copper wire of ·18 centim. diameter, surrounded by a sheathing of guttapercha ·91 centim. thick. [k for guttapercha = 2·46; one mile = 160,933 centims.]

Ans. 82,164 *units*.

3. Define "intensity of the magnetic field." A magnet whose strength is 270 is placed in a uniform magnetic field whose intensity is ·166. What are the forces which act upon its poles? *Ans.* + 45 *dynes* and — 45 *dynes*.

4. Define "intensity of magnetization." A rectangular bar-magnet, whose length was 9 centimetres, was magnetized until the strength of its poles was 164. It was 2 centimetres broad and ·5 centimetre thick. Supposing it to be uniformly magnetized throughout its length, what is the intensity of the magnetization? *Ans.* 164.

5. A certain electric motor has 100 conductors on its armature, each carrying 10 amperes. The number of lines of force passing through the armature is 500,000. Find the work (in ergs) done in one revolution of the armature.

As each conductor cuts the lines twice in one revolution the answer will be 100,000,000 *ergs*.

6. Find the torque (see Art. 136) on the armature described in the last question. Note that with the above data the torque is independent of the radius of the armature, for the force on each conductor is proportional to the strength of the field, and this is inversely proportional to the radius if N remains the same. *Ans.* $\frac{100,000,000}{2\pi}$ *dyne-centimetres*.

7. A current whose strength in "absolute" electromagnetic units was equal to 0·05 traversed a wire ring of 2 centimetres radius. What was the strength of field at the centre of the ring? What was the potential at a point P opposite the middle of the ring and 4 centimetres distant from the circumference of the ring? *Ans.* f = ·1571; V = ± 0·0421.

8. (*a*) A spiral of wire of 1000 turns carries a current of 1 ampere. Find the total magnetomotive force which it exerts. *Ans.* 1257.

(*b*) If the spiral were 1 metre in length and 1 centimetre in diameter, find the force on a unit pole placed (1) in its centre; (2) at its end. *Ans.* 12·57 *dynes* and 6·28 *dynes*.

9. What limits are there to the power of an electromagnet?

10. What is the advantage in using an iron core in an electromagnet?

11. A rod of soft iron, 0·32 cm. in diameter and 1 metre long is uniformly overwound from end to end with an insulated copper wire making 637 turns in one layer. Find (using Bidwell's data in Art. 365) what strength of poles this rod will acquire when a current of 5 amperes is sent through the coil. *Ans.* 98·9 *units*.

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$= 2250$, B for the horse-shoe $= 1{\cdot}5 \times 9000 = 13{,}50$
$\mu_2 = 900$, then ampere-turns $=$
$$90{,}000 \left\{ \frac{12}{10 \times 2250} + \frac{1{\cdot}5 \times 30}{10 \times 900} + \frac{2 \times 0{\cdot}5 \times 2{\cdot}54}{10} \right\} + 1{\cdot}25$$

21. What thickness of copper wire must be used t above magnet in order to obtain 18,930 ampere turns, ing on each cylindrical bobbin having a mean dia centimetres, if the pressure at the terminals of the intended to be 100 volts?

If r is the resistance of one turn, and s the numbe
$$r = \frac{E}{cs} = \frac{100}{18{,}930}; \text{ but we know that } r = \frac{7 \times \pi}{d^2 \times \frac{1}{4}\pi} \times 1{\cdot}6$$

Hence diameter of wire, $d = \sqrt{\frac{18{,}930 \times 7 \times 4 \times 1}{10^6 \times 100}}$
cms.

N.B.—The thickness of wire is independent of t of turns (except in so far as this affects the mean d the bobbin), but the greater the number of turns the l the number of watts expended.

22. What is the object of "polarizing" the arm magnet in a piece of mechanism, such as a relay?

23. Describe the construction of a current-balanc mode of using it.

QUESTIONS ON CHAPTER VI

1. The resistance of telegraph wire being taken a per mile, and the E.M.F. of a Leclanché cell as 1·4 *vol* how many cells are needed to send a current of 12 *mil* through a line 120 miles long; assuming that the inst circuit offer as much resistance as 20 miles of wire and that the return current through *earth* meets with ciable resistance. *An*

2. Fifty Grove's cells (E.M.F. of a Grove $= 1{\cdot}8$ *volt*) in series, and the circuit is completed by a wire whose is 15 *ohms*. Supposing the internal resistance of each 0·3 *ohm*, calculate the strength of the current.

Ans.

3. The current running through an incandescent f carbon in a lamp was found to be exactly 1 *ampere*. ence of potential between the two terminals of the l the current was flowing was found to be 30 *volts*. the resistance of the filament?

4. Define specific resistance. Taking a specific re copper as 1/642, calculate the resistance of a kilometre wire whose diameter is 1 millimetre. *Ans.*

5. On measuring the resistance of a piece of No. 30 B.W.G. (covered) copper wire, 18·12 yards long, I found it to have a resistance of 3·02 *ohms*. Another coil of the same wire had a resistance of 22·65 *ohms*; what length of wire was there in the coil? *Ans.* 135·9 yards.

6. Calculate the resistance of a copper conductor one square centimetre in area of cross-section, and long enough to reach from Niagara to New York, reckoning this distance as 480 kilometres. *Ans.* 78·8 *ohms*.

7. Find the drop in *volts* if 400 *amperes* is passed through this conductor. What would be the waste of power (in *watts*)? *Ans.* 31,520 *volts*, 12,608,000 *watts*.

8. The resistance from plate to plate in a certain electrolytic bath is 0·9 of an *ohm*. You wish to pass through it the strongest current you can get from 20 Daniell cells, each with a resistance of one *ohm*. How would you group the cells? *Ans.* 4 in series, 5 rows in parallel.

9. The specific resistance of guttapercha being $3·5 \times 10^{23}$, calculate the number of *coulombs* of electricity that would leak in one *century* through a sheet of guttapercha one centimetre thick and one metre square, whose faces were covered with tinfoil and joined respectively to the poles of a battery of 100 Daniell's cells. *Ans.* 9·7 *coulombs*.

10. Six Daniell's cells, for each of which $E = 1·05$ *volt*, $r = 0·5$ *ohm*, are joined in series. Three wires, X, Y, and Z, whose resistances are severally 3, 30, and 300 ohms, can be inserted between the poles of the battery. Determine the current which flows when each wire is inserted separately; also determine that which flows when they are all inserted at once in parallel.

Ans.	Through X	1·05	*amperes*.
	Through Y	0·1909	"
	Through Z	0·0207	"
	Through all three	1·105	"

11. Calculate the number of cells required to produce a current of 50 *milli-amperes* through a line 114 miles long, whose resistance is 12½ *ohms* per mile, the available cells of the battery having each an internal resistance of 1·5 *ohm*, and an E.M.F. of 1·5 *volt*. *Ans.* 50 cells.

12. You have 20 large Leclanché cells (E.M.F. = 1·5 *volt*, $r = 0·5$ *ohm* each) in a circuit in which the external resistance is 10 *ohms*. Find the strength of current which flows (*a*) when the cells are joined in simple series; (*b*) all the zincs are united, and all the carbons united, in parallel arc; (*c*) when the cells are arranged two abreast (*i.e.* in two files of ten cells each); (d) when the cells are arranged four abreast.
Ans. (*a*) 1·5; (*b*) 0·1496; (c) 1·2; (d) 0·702 *ampere*.

13. With the same battery how would you arrange the cells in order to telegraph through a line 100 miles long, reckoning the line resistance as 12½ *ohms* per mile?

14. Show that, if we have a battery of n given cells each of resistance r in a circuit where the external resistance is R, the strength of the current will be a maximum when the cells are coupled up in a certain number of rows equal numerically to $\sqrt{nr \div R}$.

15. Two wires, whose separate resistances are 28 and 24, are placed in parallel in a circuit so that the current divides, part passing through one, part through the other. What resistance do they offer thus to the current?

Ans. 12·92 *ohms*.

16. Using a large bichromate cell of practically no internal resistance, a deflexion of 9° was obtained upon a tangent galvanometer (also of small resistance) through a wire whose resistance was known to be 435 *ohms*. The same cell gave a deflexion of 5° upon the same galvanometer when a wire of unknown resistance was substituted in the circuit. What was the unknown resistance? *Ans.* 790 *ohms*.

17. In a Wheatstone's bridge, in which resistances of 10 and 100 *ohms* respectively were used as the fixed resistances, a wire whose resistance was to be determined was placed: its resistance was balanced when the adjustable coils were arranged to throw 281 *ohms* into circuit. What was its resistance?

Ans. 28·1 *ohms*.

18. Describe the method of using a metre bridge to measure resistances.

19. Give the proof of Foster's method of measuring small differences of resistance from the consideration of Ohm's law.

20. To find the voltage of a dynamo you connect to its brushes the ends of a German-silver wire 120 feet long, wound on an insulating cylinder, and find that when one terminal of a Daniell cell (1·05 volt) is joined to a point on the wire, and the other terminal in series with a galvanometer is connected to another point 1 ft. from the first, no deflexion is observed. What is the voltage of the dynamo? *Ans.* 126 *volts*.

21. A battery of 5 Leclanché cells was connected in simple circuit with a galvanometer and a box of resistance coils. A deflexion of 39° having been obtained by adjustment of the resistances, it was found that the introduction of 150 additional *ohms* of resistance brought down the deflexion to 22°. Assuming the galvanometer to have 140 ohms resistance, find the internal resistance of the battery. *Ans.* 10 *ohms*.

22. How are standard resistance coils wound, and why? What materials are they made of, and why?

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wire are found two points such that the fall of potential between them is equal to the volts generated between the centre and circumference of the revolving disk. By balancing these with a galvanometer Lorenz was able to calculate in absolute measure the resistance of the wire. If M be the coefficient of mutual induction between the circumference of the disk and the surrounding coil, and T the period of revolution of the disk, show that R the resistance between the points $= M \div T$.

Ans. Since N the magnetic flux through the disk $= MC$, and $E = N/T$, and $C = E/R$, it follows that $CR = MC/T$, whence $R = M/T$. Q.E.D.

QUESTIONS ON CHAPTER VII

1. A strong battery-current is sent, for a few moments, through a bar made of a piece of antimony soldered to a piece of bismuth. The battery is then disconnected from the wires and they are joined to a galvanometer which shows a deflexion. Explain this phenomenon.

2. A long strip of zinc is connected to a galvanometer by iron wires. One junction is kept in ice, the other is plunged into water of a temperature of 50° C. Calculate, from the table given in Art. 422, the electromotive-force which is producing the current. *Ans.* 690 microvolts.

3. When heat is evolved at a junction of two metals by the passage of a current, how would you distinguish between the heat due to resistance and the heat due to the Peltier effect?

4. Lord Kelvin discovered that when a current flows through iron it absorbs heat when it flows from a hot point to a cold point; but that when a current is flowing through copper it absorbs heat when it flows from a cold point to a hot point. From these two facts, and from the general law that energy tends to run down to a minimum, deduce which way a current will flow round a circuit made of two half-rings of iron and copper, one junction of which is heated in hot water and the other cooled in ice.

5. Give a curve showing the increase and decrease of the thermo-electromotive-force as a junction of iron and copper is raised from 0° C. to 400° C., and explain it by means of the thermo-electric diagram of Professor Tait.

QUESTIONS ON CHAPTER VIII

1. Calculate by Joule's law the number of calories developed in a wire whose resistance is 4 ohms when a steady current of 0·14 ampere is passed through it for ten minutes.

Ans. 11·2 *calories.*

2. Why does the platinum wire in a Cardew voltmeter, when a steady voltage is applied to it, rise to a certain temperature and then remain at that temperature without alteration?

3. Show from the definitions of the horse-power and of the watt, and from the relations between the pound and the gramme, the foot and the centimetre, that there are 746 watts in one horse-power.

4. Explain why you would expect the heat produced in a conductor to be proportional to the square of the current.

5. Describe the construction of a watt meter and explain how you would connect it up to measure the power supplied to an electric motor.

6. Explain why it is advantageous to distribute electric energy at a high voltage. There is already laid a copper main having a resistance of 0·5 of an ohm along which it is desired to transmit 4 kilowatts, and to deliver it at the far end at a pressure of 100 volts. Which would be the more efficient method of the two following, to send 40 amps. at an initial pressure of 120 volts, or to send a current at a pressure of 2400 volts, using a transformer with an efficiency of 85 per cent?

Ans. The latter method would have an efficiency of 84·9 per cent, the former of 83·3 per cent.

7. Mention some of the principles upon which supply meters have been designed.

8. An electric motor is supplied at a pressure of 100 volts: the armature resistance is 0·01 ohm. When it is supplying 20 horse-power, what is its electrical efficiency?

Ans. 98·5 per cent.

9. Show under what circumstances an electric motor is most efficient.

10. Enumerate the principal parts of an arc lamp.

11. Why in a continuous-current arc lamp is the current usually sent downwards rather than upwards?

12. Why does the filament of an incandescent lamp get hotter than the platinum leading-in wires?

13. Explain by a diagram the system of three-wire distribution; and point out its advantage over a two-wire distribution.

14. A current of 9 *amperes* worked an electric arc light, and on measuring the difference of potential between the two carbons by an electrometer it was found to be 50 volts. What was the amount of horse-power absorbed in this lamp?

Ans. 0·603 horse-power.

QUESTIONS ON CHAPTER IX

1. The reluctance of the core of a certain transformer is 0·002. Find the coefficient of mutual induction between the primary and secondary coils which have 1000 and 50 turns respectively, assuming no magnetic leakage.

Ans. 0·628 *henry.*

2. A battery current is sent through the primary of this transformer. State from Lenz's law the direction (relatively to this current) of the E.M.F.'s induced in both the primary and secondary, (*a*) when the current is starting, (*b*) when it is ceasing.

3. Foucault set the heavy bronze wheel of his gyroscope spinning between the poles of a powerful electromagnet, and found that the wheel grew hot. What was the cause of this? Where did the heat come from?

4. You try to turn a copper disk between the poles of a magnet. If you move it slowly it goes quite easily, if you try to move it quickly it resists. Why is this? What is the force required to turn it proportional to?

5. The shunt coil of a certain dynamo has a resistance of 40 ohms. It is switched on to a battery of accumulators yielding 100 volts, and one second afterwards the current has risen to 0·9825 of an ampere. Find the coefficient of self-induction of the shunt coil. Assume log 0·607 = $\bar{1}$·783 and log ϵ = 0·434.

Ans. 80 *henries.*

6. If a battery of 10 cells each of 1·4 volt and 2 ohms resistance be applied to a circuit which has a resistance of 5 ohms and inductance 0·1 henry, find what modes of grouping the cells are best (*a*) to give the largest steady current, (*b*) to give the largest current at the end of $\frac{1}{1000}$ second, (*c*) to give the largest amount of external work relatively to the weight of zinc consumed.

Ans. (*a*) 5 in series, 2 rows in parallel. (*b*) All in series. (*c*) All in parallel.

QUESTIONS ON CHAPTER X

1. What devices are employed in continuous current dynamos to obtain (*a*) a current continuously in one direction, (*b*) a current of uniform strength?

2. Apply Fleming's Rule (Art. 226) to determine which way the electromotive-forces will operate in a ring armature

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ohms, primary; 0·014 ohm, secondary. Find the coefficient of transformation, and the volts that must be applied at the primary terminals.

Ans. Coefficient of transformation is 25; volts at primary terminals 1283.

11. State the principles upon which continuous-current transformers are made. Why is it necessary to have a moving part in continuous-current transformers and not in alternate-current transformers?

12. Enumerate three distinct kinds of alternate-current motors, and state which kind is synchronous and which not.

13. An alternate-current synchronous motor is supplied from the street mains. It is found that when fully loaded it takes more current than when lightly loaded, though it always goes at the same speed and the volts remain constant. Explain how this comes about.

14. How can you produce a rotatory magnetic field? Describe some of its properties.

QUESTIONS ON CHAPTER XI

1. It is found that a single Daniell's cell will not electrolyze acidulated water, however big it may be made. It is found, on the other hand, that two Daniell's cells, however small, will suffice to produce continuous electrolysis of acidulated water. How do you account for this?

2. From the table of electro-chemical equivalents (Art. 240) calculate how many coulombs it will take to deposit one grain of the following metals:—Copper (from sulphate), silver, nickel, gold. *Ans.* Cu 3058, Ag 891, Ni 3286, Au 1473.

3. A battery of 2 Grove cells in series yields a current of 5 amperes for 2 hours; how much zinc will be consumed, assuming no waste? *Ans.* 24·26.

4. Calculate the E.M.F. of a Daniell cell from considerations of the heat value of the combinations which take place and the quantity of the elements consumed, taking the heat value for zinc in sulphuric acid as 1670 and that for copper as 909·5.

Ans. 1·11 *volts.*

5. Describe the construction and working of a modern secondary battery.

6. Most liquids which conduct electricity are decomposed (except the melted metals) in the act of conducting. How do you account for the fact observed by Faraday that the amount of matter transferred through the liquid and deposited on the electrodes is proportional to the amount of electricity transferred through the liquid?

7. Describe the process for multiplying by electricity copies of engravings on wood-blocks.

8. How would you make arrangements for silvering spoons? of nickel-bronze by electro-deposition?

QUESTIONS ON CHAPTER XII

1. Sketch an arrangement by which a single line of wire can be used by an operator at either end to signal to the other; the condition of working being that whenever you are not sending a message yourself your instrument shall be *in circuit* with the line wire, and *out of* circuit with the battery at your own end.

2. What advantages has the Morse instrument over the needle instruments introduced into telegraphy by Cooke and Wheatstone?

3. Explain the use and construction of a relay.

4. Show, from the law of traction (Art. 384), that the *change* of attracting force resulting from a *change* in the number of magnetic lines that enter an armature will be greater if the system is polarized (*i.e.* magnetized to begin with) than if it is non-polarized.

> *Ans.* Since $f \propto N^2$, it follows that $f + df$ will be proportional to $(N + dN)^2$. Expanding, and subtracting the former, and neglecting the small term $(dN)^2$, we find $df \propto 2N \cdot dN$; which shows that, for a given dN, $df \propto N$.

5. It is desirable in certain cases (duplex and quadruplex signalling) to arrange telegraphic instruments so that they will respond only to currents which come in one direction through the line. How can this be done?

6. It is wished to make a sort of duplex telegraph by using one set of instruments that work with continuous currents, the other set with rapidly alternating currents, at the same time on the same line. To carry out this idea there must be found (*a*) an apparatus which will let continuous currents flow through it, but will choke off alternate currents; (*b*) an apparatus which will transmit alternate currents, but cut off continuous currents. What apparatus will do these things?

7. A battery is set up at one station. A galvanometer needle at a station eighty miles away is deflected through a certain number of degrees when the wire of its coil makes twelve turns round the needle; wire of the same quality being used for both line and galvanometer. At 200 miles the same deflexion is obtained when twenty-four turns are used in the galvanometer-coil. Show by calculation (*a*) that the internal

resistance of the battery is equal to that of 40 miles of the line-wire; (*b*) that to produce an equal deflexion at a station 360 miles distant the number of turns of wire in the galvanometer-coil must be 40.

8. Suppose an Atlantic cable to snap off short during the process of laying. How can the distance of the broken end from the shore end be ascertained?

9. Suppose the copper core of a submarine cable to part at some point in the middle without any damage being done to the outer sheath of guttapercha. How could the position of the fault be ascertained by tests made at the shore end?

10. Explain the construction and action of an electric bell.

11. Describe and explain how electric currents are applied in the instruments by which very short intervals of time are measured.

QUESTIONS ON CHAPTER XIII

1. Explain the use of Graham Bell's telephone (1) to transmit vibrations; (2) to reproduce vibrations.

2. Describe a form of telephone in which the vibrations of sound are transmitted by means of the changes they produce in the resistance of a circuit in which there is a constant electromotive-force.

3. Two coils, A and B, of fine insulated wire, made exactly alike, and of the same number of windings in each, are placed upon a common axis, but at a distance of 10 inches apart. They are placed in circuit with one another and with the secondary wire of a small induction-coil of Ruhmkorff's pattern, the connexions being so arranged that the currents run round the two coils in opposite directions. A third coil of fine wire, C, has its two ends connected with a Bell's telephone, to which the experimenter listens while he places this third coil between the other two. He finds that when C is exactly midway between A and B no sound is audible in the telephone, though sounds are heard if C is nearer to either A or B. Explain the cause of this. He also finds that if a bit of iron wire is placed in A silence is not obtained in the telephone until C is moved to a position nearer to B than the middle. Why is this? Lastly, he finds that if a disk of brass, copper, or lead is interposed between A and C, the position of silence for C is now nearer to A than the middle. How is this explained?

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